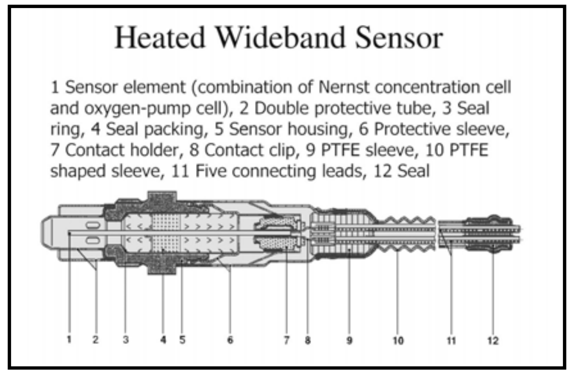
Application Note 19:
New Fuel Control Strategies Enabled by Innovate's "Direct Digital" Wideband Controls

Summary

Oxygen sensors are critical components in every internal combustion vehicle on the road. Innovate's unique approach (aka "Direct Digital") can be used to control oxygen sensors in a manner that differs greatly from traditional, mostly analog, technologies.

This, in turn, enables new strategies in fuel controls. While the initial commercial acceptance of the Innovate technology has been in the performance aftermarket, the biggest gains will be realized in the OEM market, where factory-original ECUs can be designed and programmed to utilize Direct Digital wideband technology.

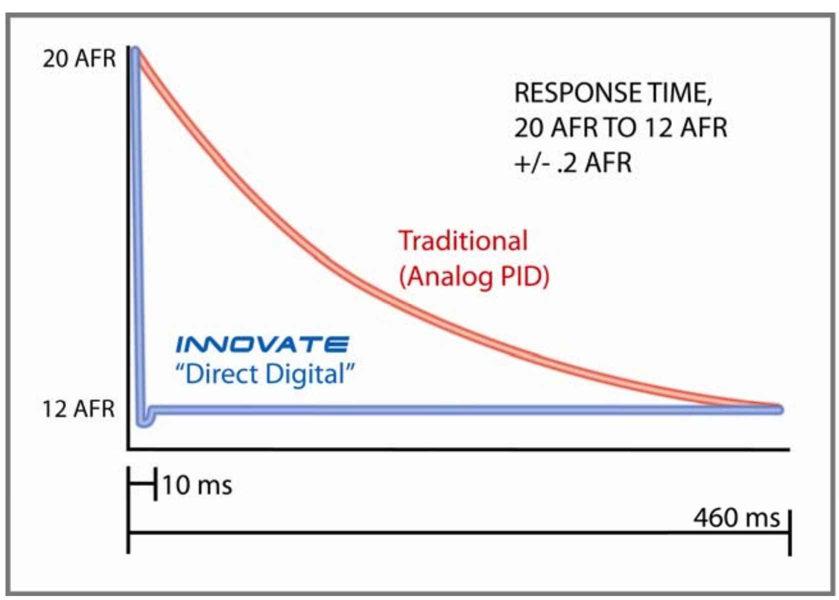
Background



Current Innovate products use the same wideband zirconium-dioxide oxygen sensors as current production vehicles, but the ***control methodology*** is completely different. US Patent #6,978,655, titled "System, Apparatus, and Method for Measuring an Oxygen Concentration of a Gas," fully details the inventions summarized below.

The Innovate measurement principle does not use the regular PID (proportional-integral-derivative) feedback mechanism to control the wideband sensor. Instead, the pump current is positive until the reference (Nernst) cell shows < Lambda 1 in the measurement chamber of the wideband. Then the polarity of the pump current is reversed until the reference cell shows > Lambda 1. This is done with a small hysteresis. This way the measurement gas in the measurement chamber oscillates at about 100-500 Hz around stoichiometric. The oscillation frequency depends on the constant (but changing polarity) pump current, hysteresis, the sensor itself, and Lambda. The frequency has a max at Lambda 1. This is basically a 2-point regulator, or in digital electronic terms, the operating principle of a delta-sigma analog to digital converter, except that here the analog value measured is directly the exhaust gas.

The duty cycle PWM of that oscillation is calculated with (t1 - t2) / (t2 + t2), therefore has a range of +/- 1.0. t1 is the duration of positive polarity of pump current, t2 the duration during negative current polarity. Both measured with 16 bit accuracy. With PWMair (duty cycle in air) the O2 flow rate of the pump cell can be directly calculated with PWM / PWMair and therefore Lambda can be calculated from that. Because the sensor is only used with constant and relative high Ip, but with changing polarity, PWM is completely linear with O2 flow, and independent of the Lambda/Ip curve of a particular sensor after normalizing to PWMair. Because of the oscillation, there is no equilibrium state in the cell which would slow down the diffusion. Also because of the oscillation, there is no electrostatic charge buildup on the measurement cell that causes drifts during operation at Lambda < 1.0.



The Lambda/Ip curve of a wideband sensor has a singularity at Lambda 1.0. This causes instabilities in the normal PID feedback mechanism. The Innovate method does not show those instabilities. A conventional PID feedback loop needs to be tuned to the speed response of the controlled system. The best one can do is to achieve critical damping, otherwise it would lead to wild oscillations and over swings. The Innovate principle approach basically makes specific use of those by running the feedback loop deep into those normally undesired oscillations.

In a conventional PID feedback wideband controller the temperature is regulated via the AC impedance of the reference cell (usually measured with a small AC current of 1-4 kHz). This measurement frequency has to be filtered back out of the reference cell signal with low pass filters and that cause further latency in the measurement loop.

The Innovate system uses the AC impedance of the pump cell, which shows the same temperature behavior as the reference cell. With the Innovate measurement principle already essentially impresses an AC current on the pump cell, it's possible to measure its temperature for temperature regulation without any further hardware costs.

A further slowdown of the conventional PID measurement loop of a wideband comes because many wideband controllers drive the pump cell with a low impedance voltage source (op-amp output) directly. The pump current is then measured with a measurement resistor. But the pump cell in a wideband acts also like a Nernst cell that produces a counter EMF that's dependent on the Lambda value in the measurement chamber. This counter EMF is essentially shorted by the low impedance source and then causes a reduction of the pump current during Lambda transitions, which is in turn compensated by the changing error value in the reference cell. This means, in a regular PID implementation of the measurement loop of a conventional wideband controller, many (often hundreds) loop passes are made through the delay between pump cell and reference cell. With the Innovate "2-point regulator" implementation only two passes are needed for a complete Lambda measurement as Lambda can be calculated after every oscillation period. This is the major reason the Innovate measurement principle is so fast.

Response Time

The fast response time of Direct Digital technology enables new fuel control strategies. The biggest impact is in two areas:

1) **Rapid load-transition Periods.** Due to the slow response time of PID systems, even the most sophisticated modern vehicles must go "open-loop" for up to 500ms second after major throttle transitions (for example, "Acceleration Enrichment" period). Such open-loop operation often results in excessive fuel injection (and therefore reduced MPG, and increased emissions) during transitions. In most regular driving, transitions are quite frequent. It is estimated that **eliminating open-loop operation acceleration enrichment** improves average fuel economy by as much as 7%, and reduces emissions by the same amount.
2) **Injector balancing.** OEMs allow up to 5% cylinder-to-cylinder variation in new fuel injectors. This is less than ideal to begin with, as some cylinders will be lean (producing excessive NOx), and some will be rich (producing excessive CO). The real problem however, is that this condition deteriorates over time (injector clogging, etc.). Cylinder-to-cylinder variation climbs to 10% or more, stressing the catalytic converter, damaging engines, and producing excess emissions. Direct Digital technology is fast enough to enable a **single sensor to detect *individual-cylinder* lambda** as the "slugs" of exhaust pass the sensor. This allows the ECU to vary each injector's duty cycle, and precisely manage each cylinder.

The benefits of full-time closed-loop operation are clear- essentially you have a self-tuning, adaptive engine that can handle major variations in fuel composition, barometric pressure, and component aging. However, until Direct Digital, many of the gains from closed-loop operation were unattainable.

Full-time closed loop functioning does not preclude the ECU from building and maintaining a safe "fallback" fuel map. If an oxygen sensor fails during normal operation, the ECU will then be merely as smart as the best current ECU.

Conclusion

Designers of new fuel-control systems should fully explore the benefits of implementing full-time, closed-loop injection strategies based on Direct Digital Wideband systems.