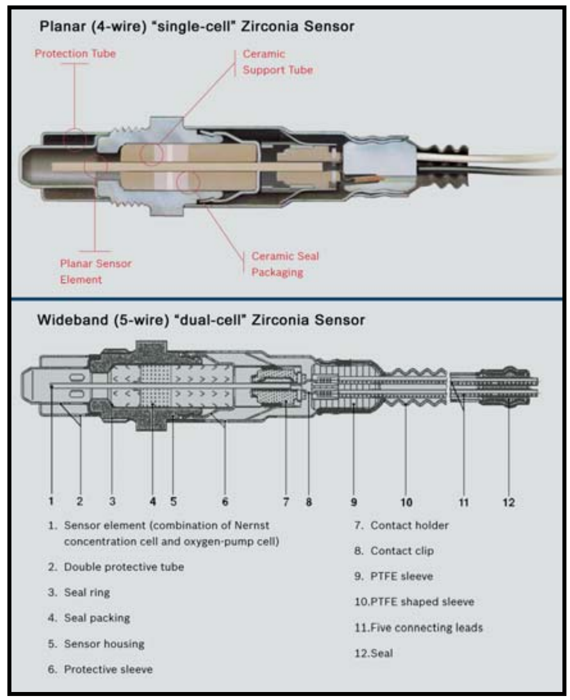
Application Note 23:
Engine Control Strategies Enabled by Innovate's "Direct Digital" Wideband Technology

Summary

Oxygen sensors are critical components in most internal combustion engines today. Innovate's "Direct Digital" technology enables a new generation of oxygen sensors that are **faster, more accurate, more reliable, and lower cost** than the best current wideband oxygen sensors.

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

Background: A Brief History of the Zirconia Oxygen Sensor



Zirconia sensors have been in use in production automobiles since the mid 1970's. The first sensors were "unheated thimble" designs with 1or 2 wires. The early 80's saw the introduction of "heated thimble" designs that came up to temperature faster, and had 3 or 4 wires. 4-wire "planar" sensors started being used in the late 90's and now account for more than 50% of all new platforms, in part due to low cost and high reliability. "Wideband" 5-wire sensors (heated, planar, dual-cell) are the newest and are required for high-performance, direct-injection, stratified charge, flex-fuel, ULEV, and other demanding applications. Factors that have slowed the adoption of wideband sensors include high manufacturing cost and reliability issues.

Although the Direct Digital control methodology was originally developed with wideband oxygen sensors, perhaps the biggest breakthrough is that it enables **a new generation of sensors** that combine the low cost and high reliability of 4-wire planar sensors, while matching the accuracy range, and *exceeding* the responsiveness of the best current wideband sensors.

The Technology

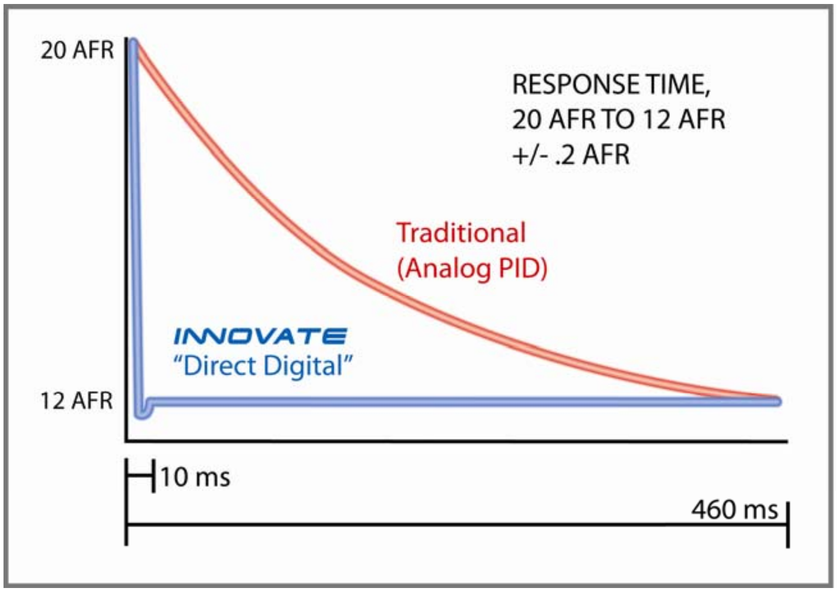
US Patent #6,978,655, titled "System, Apparatus, and Method for Measuring an Oxygen Concentration of a Gas," fully details the inventions summarized below.

With the Innovate measurement principle, a single Nernst cell can function as BOTH pump and reference cell. Direct Digital 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 shows < Lambda 1. Then the polarity of the pump current is reversed until the reference shows > Lambda 1. This is done with a small hysteresis. This way the measurement gas in the measurement chamber oscillates at 300-800 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 Direct Digital approach basically makes specific use of those by running the feedback loop deep into those normally undesired oscillations.

An additional downside of the conventional PID measurement loop of a wideband arises 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 one can have self-tuning, adaptive engines that can handle major variations in fuel composition, compression ratios, barometric pressure, and component aging. However, until Direct Digital, many of the gains from closed-loop operation were not easily unattainable.