

Estimation of Individual Cylinder Fuel Air Ratios from a Switching or Wide Range Oxygen Sensor for Engine Control and On-Board Diagnosis

2011-01-0710

Published
04/12/2011Zhijian James Wu and Bryon Wasacz
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doi:10.4271/2011-01-0710

ABSTRACT

The fuel air ratio imbalance between individual cylinders can result in poor fuel economy and severe exhaust emissions. Individual cylinder fuel air ratio control is one of the important techniques used to improve fuel economy and reduce exhaust emission. California Air Resources Board (CARB) also has required automotive manufacturers to equip with on-board diagnosis system for cylinder fuel air ratio imbalance detection starting in 2011. However, one of the most challenging tasks for the individual cylinder fuel air ratio control and cylinder imbalance diagnosis is how to retrieve the cylinder fuel air ratio information effectively at low cost. This paper presents a novel and practical signal processing based fuel air ratio estimation method for individual cylinder fuel air ratio balance control and on-board fuel air ratio imbalance diagnosis. Based on temporal array signal processing techniques, an array of data samples from an oxygen sensor located in a confluence point of runners is fed into each cylinder's linear, non-linear, or neural network estimator to estimate its fuel air ratio. This method works with both wide range oxygen sensors and switching oxygen sensors. This paper presents in more detail the linear estimation method and the vehicle test results due to its advantages of good performance, low computational load, and easily automated calibration for production.

INTRODUCTION

The fuel air ratio imbalance between individual cylinders can result in poor fuel economy and severe exhaust emissions. Individual cylinder fuel air ratio control is one of the important techniques used to improve fuel economy and reduce exhaust emission. California Air Resources Board (CARB) also has required automotive manufacturers to equip

with on-board diagnosis system for cylinder fuel air ratio imbalance detection starting in 2011.

To effectively control individual cylinders' fuel air ratio balance and diagnose the fuel air ratio imbalance, individual cylinders' fuel air ratio information is necessary to be available. The simplest method to retrieve the information is to directly measure the fuel air ratios by installing wide range O₂ sensors inside each runner that is connected to its exhaust manifold. However, this method is not practical and affordable for mass production.

One of the most challenging tasks to control the individual cylinder fuel air ratio and diagnose cylinder imbalance is retrieving the cylinder fuel air ratio information effectively and accurately at low cost. In the past two decades, a majority of the researchers used O₂ sensors, especially wide range O₂ sensors, as the signal sources [1],[2],[3],[4],[5],[6],[7],[8],[9], some studies focused on other sources, for example, ion currents [10]. The typical O₂ signal methods are based on a physical or mathematical model of the exhaust manifold and O₂ sensor. The model is usually described as a state system with the measurements of a wide range O₂ sensor at the confluence point as its input. Finally, the Kalman filtering technique is applied to the state system to predict or estimate the individual cylinder fuel air ratio information. The performance of this kind of method depends on the accuracy and robustness of the developed models and the determination of the model coefficients. To establish a good model and determine the coefficients effectively and efficiently is very challenging. In real applications with various engine operating conditions, the exhaust gas flows are very complex and usually nonlinear and time-varying. The high computational requirement for Kalman filtering is another difficulty for most production engine controllers.

Paper [7] presents a different method to extract fuel air ratio information from a switching O₂ sensor. In the method, the O₂ signal is filtered using a high pass filter. It is assumed that there is no gas coupling. The filtered signal is then separated into multiple signal sequences. An open-loop fuel perturbation and signal sequence comparison procedure is used to select the signal sequence that is most aligned to a cylinder. The alignment becomes necessary for the method because each cylinder related signature in the filtered signal has variable delays due to gas flow characteristics in the exhaust system. Because of the assumption, a high computational requirement for Kalman filtering is avoided and it becomes more practical for real applications. With this method, the obtained fuel air ratio information is a relative quantity, not the estimate of the actual fuel air ratio or its deviation to the stoichiometric point. That is, the quantity may not be the same in different engine speed and load conditions even for the same level of fuel air ratios. In many real situations, the assumption will not be well satisfied. This will degrade the performance and the extracted quantities of each cylinder will not maintain a proper proportion of their true fuel air ratios of the cylinders.

This paper presents a novel and practical signal processing based fuel air ratio estimation method used for individual cylinder fuel air ratio balance control and on-board fuel air ratio imbalance diagnosis. Based on the temporal array signal processing technique, an array of data samples from an oxygen sensor located in a confluence point of runners is fed into each cylinder's linear, non-linear, or neural network estimator to estimate its actual fuel air ratio. This method works with not only wide range oxygen sensors but also switching oxygen sensors. This paper presents in more detail the linear estimator method and the vehicle test results due to its advantages of good performance, low computational load, and easily automated calibration for production. To understand the linear estimator's capability, the neural network estimators' results have been used for comparison.

The discussions in the paper include the following topics:

- O₂ sensors and cylinder imbalance signals;
- Array signal processing based individual cylinder fuel richness estimation;
- Vehicle data test results.

O₂ SENSORS AND CYLINDER IMBALANCE SIGNALS

Oxygen sensors are widely used in modern engine vehicles today. Typically, one O₂ sensor is installed at the confluence point of exhaust manifold's runners for each bank. It is in front of the catalytic converter and is usually called as upstream O₂ sensor. Another one is installed after the catalytic converter and is called downstream O₂ sensor. The upstream O₂ sensor is used to retrieve the cylinder fuel air ratio imbalance signals.

In many applications, the use of the normalized fuel air ratio is more convenient than the use of the fuel air ratio itself. In the following discussion, we will use a quantity of the normalized fuel air ratio that deviates to the stoichiometric point and call it as the fuel richness. It is defined as:

$$\begin{aligned}\text{Fuel Richness} &\triangleq \Delta\phi = (\phi - 1) \times 100 \\ &= (14.64 F/A - 1) \times 100\end{aligned}\quad (1)$$

where $\phi = 14.64 F/A$ is the normalized fuel air ratio and 14.64 is the stoichiometric number. Thus, the fuel air ratio estimation is equivalent to the fuel richness estimation. $\Delta\phi = 0$ means the fuel air ratio is balanced. $\Delta\phi > 0$ indicates that fuel is rich, and $\Delta\phi < 0$ that the fuel is lean.

Currently, there are two kinds of oxygen sensors used in the automotive applications: switching O₂ sensors and wide range linear O₂ sensors. They are quite different in the sensors' mechanisms, responses, usages and costs. Although wide range linear O₂ sensors have been used in vehicles, in particular, for upstream O₂ sensors, switching O₂ sensors are still the most popular in vehicles mainly due to its low cost.

Figure 1 shows an example of a V6 engine bank 2's switching O₂ signals with various percentages of fuel richness induced. When an engine operates in closed loop O₂ fuel control, the upstream switching sensor's wave form is a sinusoid type of switching wave. If the fuel air ratio of all individual cylinders is balanced and no fuel richness is induced, the switching wave is smooth, as shown in the top plot. However, when 5% and 10% fuel richness are induced in Cylinder 2, the switching waves are no longer smooth and are distorted as shown in the 2nd and 3rd plot from the top. When 20% fuel richness is induced in Cylinder 2, the switching wave is severely distorted and becomes difficult to identify, as shown in the bottom plot. **Figure 2** shows a V8 engine bank 2's wide range O₂ signals with no fuel richness induced and 10% and 20 fuel richness induced, respectively.

Because of the switching sensor's nonlinear characteristics, generally it is more difficult to estimate the fuel air ratios from it than from a wide range sensor. Most research focuses on the estimation from wide range O₂ sensors. This paper focuses on the estimation from a switching O₂ sensor. First, the switching O₂ sensor is still the most popular in vehicles mainly due to its low cost. Secondly, the presented method works with the wide range O₂ sensor as well as the switching O₂ sensor.

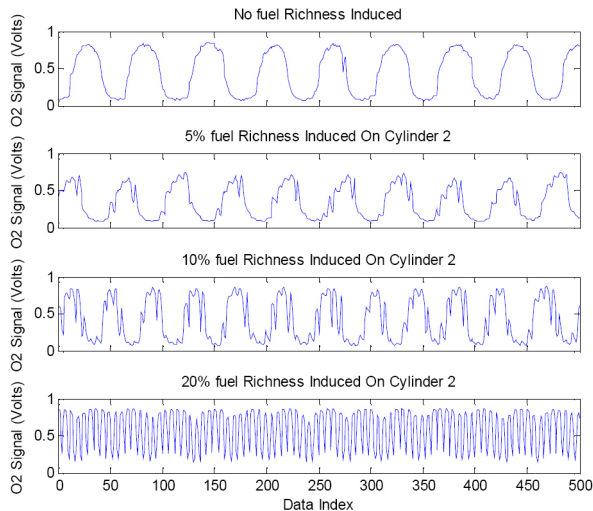


Figure 1. V6 engine bank 2's switching O2 signals with 0, 5, 10 and 20% of fuel richness induced.

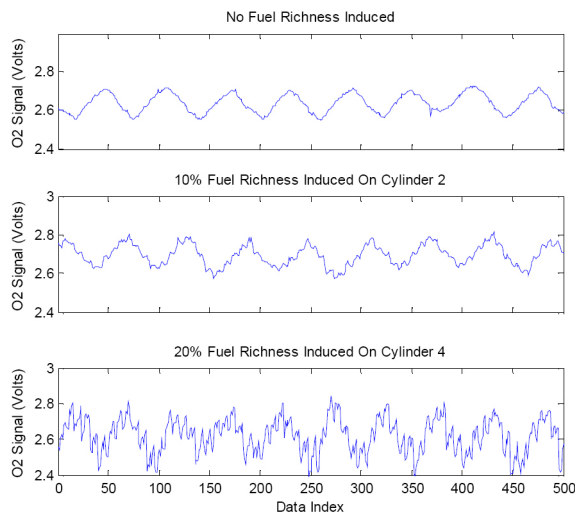


Figure 2. V8 engine bank 2's wide range O2 signals with 0, 10 and 20% of fuel richness induced.

To understand the switching O2 sensor's nonlinear characteristics, [Figure 3](#) illustrates the relationship of the input and output signals. [Figure 3.a](#) shows the sensor working in the linear area of the switching sensor's transfer curve. The input signal is a sine wave with small amplitude and is represented as the fuel air imbalance. The output signal has no nonlinear distortion. [Figure 3.b](#) shows the sensor working in the nonlinear area of the switching sensor's transfer curve. The input signal is the same signal as in [Figure 3.a](#), but it has been superimposed on a very slow sine wave. This is similar to the switching mode of closed loop fuel control. The output signal has been severely distorted in the nonlinear areas. In the slow signal's peak and valley areas, the output is very small. It is the switching O2 sensor's nonlinear transfer characteristics that make it difficult to estimate the fuel air ratio from the switching sensor in a large fuel air ratio range.

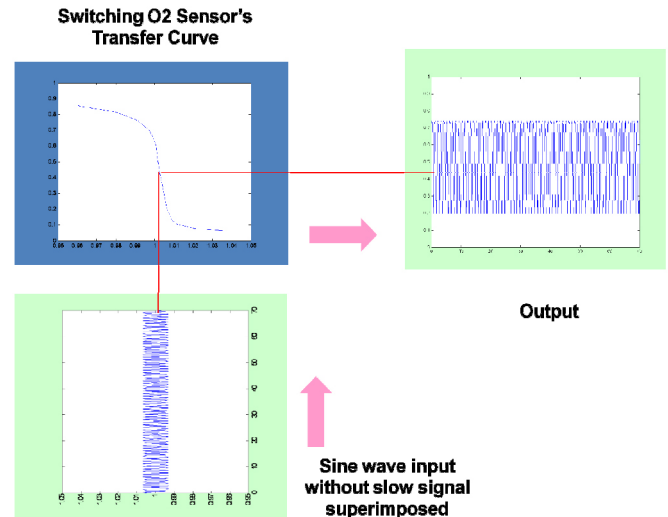


Figure 3.a. Illustration of the relations of the input and output when a switching sensor works in a linear mode.

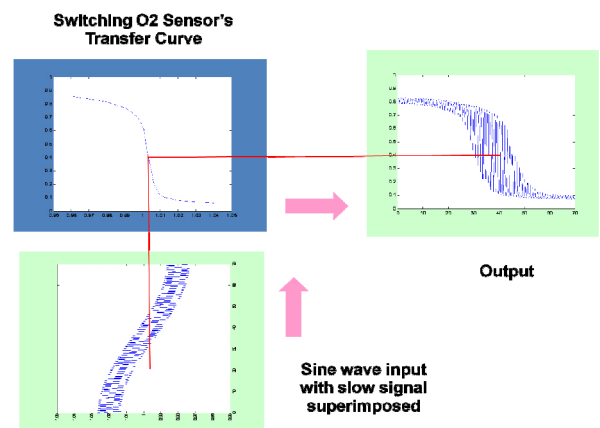


Figure 3.b. Illustration of the relations of the input and output when a switching sensor works in a nonlinear mode.

To improve the fuel richness estimation, a linearization processing is applied to the raw switching O2 signal in the study. This requires finding a nonlinear function, i.e., the inverse of the switching sensor's transfer function. It can be obtained from the O2 sensor suppliers' O2 output voltage and A/F data or curves. In this study, a polynomial function is generated from the Voltage-A/F data and is applied to raw O2 data to reduce the impact of the switching O2 sensor's nonlinear characteristics. The linearized O2 signal is expressed as

$$x(n) = a_0 + a_1(O_2(n) - c) + \dots + a_N(O_2(n) - c)^M \quad (2)$$

where $O_2(n)$ is the raw O2 signal, n is the sampling index, c is a constant, a_i , $i = 0, \dots, M$, are the coefficients of the polynomial of M degrees. The benefits of the linearization will be discussed in the following section of vehicle data test results.

ARRAY SIGNAL PROCESSING BASED INDIVIDUAL CYLINDER FUEL RICHNESS ESTIMATION

The basic idea presented in this paper for the individual cylinder fuel richness estimation is based on a virtual sensing concept as illustrated in Figure 4.a. For each cylinder in an exhaust manifold, there is a fuel richness estimator using an O2 signal as its input. The O2 sensor is located at the confluence point of a bank's runners. The estimators have parameters that are determined or calibrated based on the true measurements from the wide range O2 sensors at each runner. These wide range O2 sensors are used only for calibration and are not used in production vehicles.

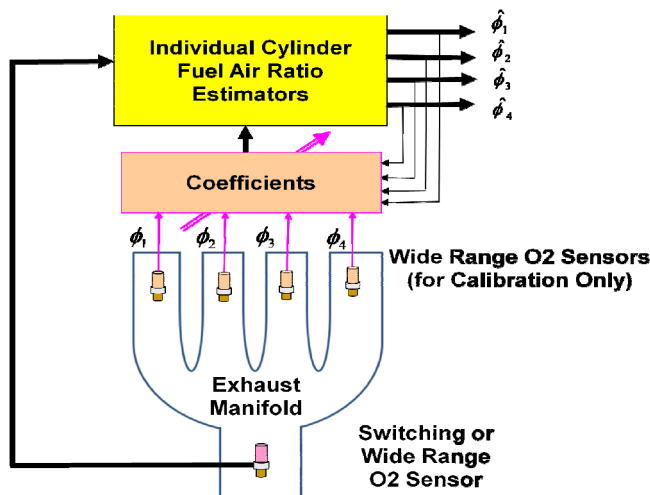


Figure 4.a. Virtual sensing concept for individual cylinder fuel richness estimation. The wide range O2 sensors at each runner are installed for identification of the fuel richness estimators' coefficients.

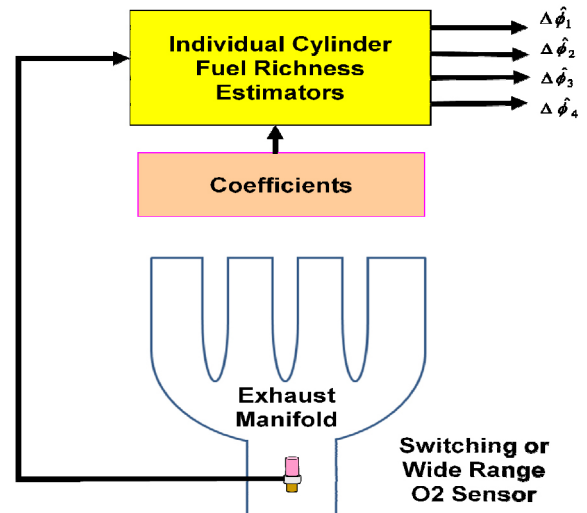


Figure 4.b. The fuel richness estimators with identified coefficients are used in production vehicles for fuel richness estimation.

Figure 5 shows a system block diagram of the individual cylinder fuel air ratio control and individual cylinder fuel air ratio imbalance on-board diagnoses (OBD). The system's major input signal is the O2 signal measured at confluence point for a given exhaust manifold bank. The engine speeds (RPM) and the engine-load representative signal, manifold absolute pressures (MAP), are used to define the estimation zones. The estimators' parameters may depend on the operating zones. Cylinder ID is for synchronization of the estimation results with the engine cylinder ID. The system consists of four major function blocks. The first block is to estimate the individual cylinder's fuel richness, and is the most critical part. It is also the main part discussed in the paper. The individual cylinder imbalance decision is made by comparing each cylinder's fuel richness and the preset thresholds in the detection block. The thresholds are determined in terms of emission requirements. Based on the cylinder imbalance decision and CARB's rules, the malfunction light will be turned on or off, as shown in the bookkeeping block. The estimated individual fuel richness is used to adjust fuel multipliers of each cylinder for individual cylinder fuel air ratio control. Because the estimates of each cylinder's actual fuel richness, not the relative values, are obtained, the control strategy will become simpler and more effective.