

Determine Air-Fuel Ratio Imbalance Cylinder Identification with an Oxygen Sensor

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ABSTRACT

Air-fuel ratio cylinder imbalance is a condition where the air-fuel ratio in one or more cylinders is different than the other cylinders. When air-fuel ratio cylinder imbalance occurs in one or more cylinders the fuel delivery system is unable to maintain a proper vehicle emission level.

It is required for on-board diagnostics to detect air-fuel ratio cylinder imbalance levels which cause the fuel delivery system to be unable to maintain vehicle emissions at or below 1.5 times of any of the applicable FTP (Federal Test Procedure) emission standards. Currently California Air Resources Board (CARB) only requires on-board diagnostics to detect exhaust bank specific air-fuel ratio cylinder imbalance. In the near future CARB will require on-board diagnostics to detect cylinder specific air-fuel ratio cylinder imbalance. This paper presents a non-intrusive approach on determining single cylinder air-fuel ratio imbalance identification (ID) with an oxygen sensor. It employs digital filtering technique to extract the air-fuel ratio cylinder imbalance signals from existing upstream oxygen sensor voltage signals on single or dual exhaust bank engines. The filtered oxygen sensor voltage signals are processed with mathematical manipulation in order to determine the imbalanced cylinder. The oxygen sensor can be a binary or wide range type, however only the binary type is considered here. Different filter coefficients should be used for different types of oxygen sensors.

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INTRODUCTION

Oxygen sensors are widely used in engine controls and on-board diagnosis. [Figure 1](#) shows a typical dual exhaust bank configuration. The upstream oxygen sensor is the one closest to the engine and the downstream oxygen sensor is the one furthest from the engine, located after the catalytic converter. The primary purpose of upstream oxygen sensors is to give the ECM (Engine Control Module) input on air-fuel ratio by comparing how much oxygen is in the exhaust to the ambient air outside of the sensor.

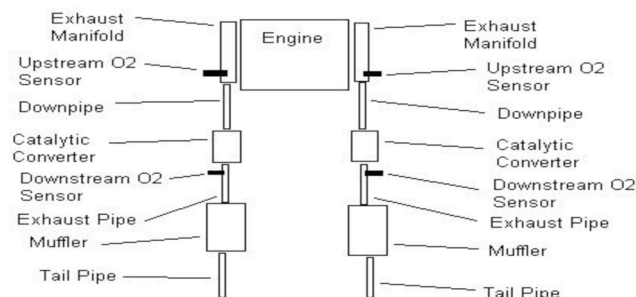


Figure 1. A typical dual exhaust bank configuration

The voltage of the upstream oxygen sensor has been used for this experiment to identify the imbalanced cylinder. Engine exhaust gas transport delay cylinder event count has been utilized for identifying imbalanced cylinder ID in the experiment. The exhaust gas transport delay is the time it takes for the charge mixture to move from the injection point, through the engine and exhaust system to the upstream oxygen sensor.[1] In theory, the exhaust gas transport delay is the function of engine speed and intake manifold pressure. The exhaust gas transport delay cylinder event count is the number of cylinder firing events it takes for the charge mixture to move from the injection point, through the engine and exhaust system to the upstream oxygen sensor.

ALGORITHM OVERVIEW

[Figure 2](#) shows an overview of the algorithm for identifying the air-fuel ratio imbalanced cylinder. There are five functional blocks. They are Oxygen sensor voltage signal sampling, Oxygen sensor signal filtering, Process filtered oxygen sensor signal, Determine rich/lean imbalance status and Determine imbalanced cylinder ID.

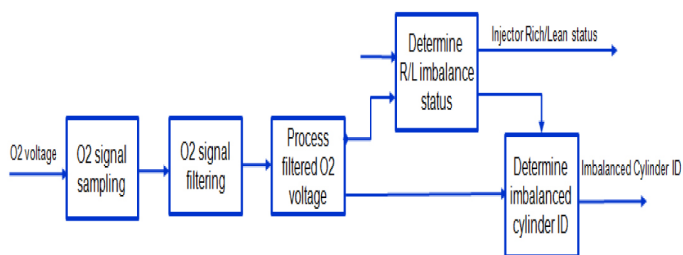


Figure 2. Overview of determining air-fuel ratio imbalance cylinder identification

Functional Description

Oxygen Sensor Signal Sampling

All functions to determine air-fuel ratio imbalance cylinder ID are executed either at engine cylinder firing event rate or engine cycle rate. For a better signal-noise ratio, oxygen sensor signal sampling rate should follow Nyquist rate which is twice the maximum component frequency of the function being sampled. For a dual exhaust bank configuration, oxygen sensor signal is sampled at every engine cylinder firing event. For a single exhaust bank, the sampling rate should be doubled.

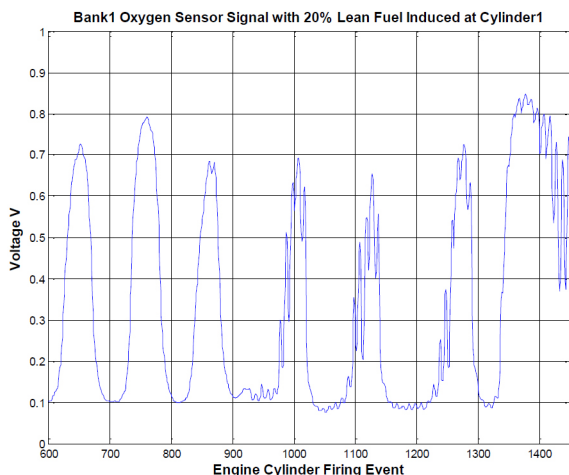


Figure 3. Oxygen sensor signal with 20% lean fuel imbalance induced at engine firing event sampling rate

Figure 3 shows Bank1 oxygen sensor voltage signal. At 900 cylinder firing events, the 20% lean fuel imbalance was induced on cylinder1. The X-axis indicates the number of cylinder firing events, and Y-axis indicates the O2 sensor voltage.

The 20% lean imbalance was selected based on experimental emissions results that exceeded the engineering target of 1.3 times of the FTP emissions standards.

Figure 4 shows the same system. At 930 cylinder firing events, a 20% rich fuel imbalance was induced on cylinder1. The X-axis indicates the number of cylinder firing events, and Y-axis indicates the O2 sensor voltage.

The 20% rich imbalance did not show a large impact on vehicle emissions. It is used for demonstration purposes in this experiment.

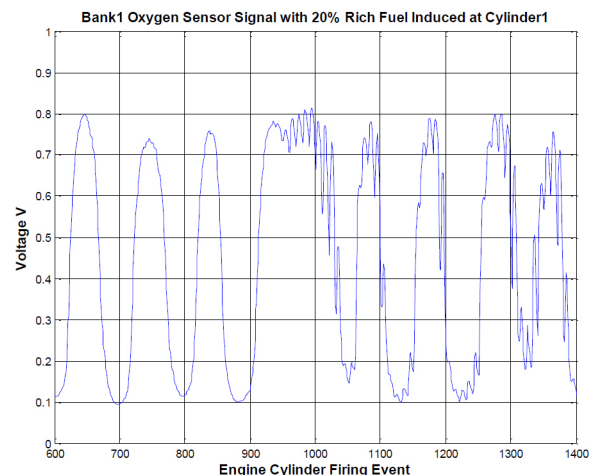


Figure 4. Oxygen sensor signal with 20% rich fuel imbalance induced at engine firing event sampling rate

Oxygen Sensor Signal Filtering

An order based spectrum analysis and filtering technique have been used in the oxygen sensor filter design. Orders are harmonics of the rotational speed, and therefore evaluating orders can be critically important on many types of rotating machines. [2] Filtered orders provide another method for evaluating rotational speed harmonics. Filtered orders apply a band-pass tracking filter to the signal and filter out everything not related to the order of interest. This method is similar to the tracking filters used in sine testing or rotor dynamics analysis. [2] The advantage of an order based filter is that it is independent of engine speed and engine load.

The digital filter used for filtering oxygen sensor voltage is a band-pass Finite Impulse Response (FIR) filter. It also removes low frequency and DC (Direct Current) components, such as oxygen sensor response time delay. In general the oxygen sensor response time delay is not a function of engine speed and engine load. It can be considered as a constant value in a driving cycle.

For a discrete-time FIR filter of order N, each value of the output sequence is a weighted sum of the most recent input values. For a one-dimensional digital filter, the mathematical formula of normalized filter coefficients is as the following:

$$y[n] = b_0x[n] + b_1x[n-1] + \dots + b_Nx[n-N] = \sum_{i=0}^N b_i x[n-i]$$

where: y is filter output, x is filter input, b is filter coefficients, n is number of samples or filter length, N is the filter order. For Nth-order filter, there are (N + 1) terms.

In this case, x is oxygen sensor voltage input signal, and y is filtered oxygen sensor voltage. For a better filter result, the filter length applied was equal to five engine cycles plus one. For a 10-cylinder engine, the filter length is 51.

Figure 5 shows filtered oxygen sensor voltage signal with 20% lean fuel imbalance induced on cylinder1. The input is the same as oxygen sensor voltage as in Figure 3. The filter attenuates the normal oxygen sensor signals, and amplifies lean imbalance signals. It shows

that there is very good separation between normal oxygen sensor voltage signal and lean imbalanced oxygen sensor voltage signal. For 20% rich fuel imbalance induced, filtered oxygen sensor voltage signals shows a similar result as in Figure 5.

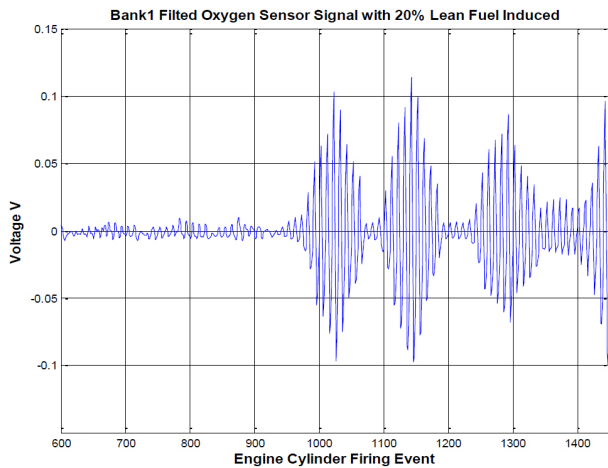


Figure 5. Filtered oxygen sensor voltages with 20% lean fuel imbalance induced at Cylinder 1

Process Filtered Oxygen Sensor Voltage

There are three tasks in this process.

Updating Filtered Oxygen Sensor Voltage Buffer

There are two filtered oxygen sensor voltage buffers for a dual exhaust bank engine configuration, and one for a single exhaust bank configuration. The buffer index has to be synchronized with the cylinder firing order index in order to determine the correct air-fuel ratio imbalance cylinder ID. For a dual exhaust bank, the filtered oxygen sensor voltage is stored in *Bank1 Filtered Oxygen Sensor Voltage Buffer* if cylinder firing order index indicates bank1, otherwise it is stored in bank2. The buffer is updated at engine cylinder firing event rate.

Determining Imbalance Detection Threshold

Air-fuel ratio imbalance detection threshold is a calibration which is a function of engine speed and engine load. The air-fuel ratio imbalance detection threshold is directly related to the vehicle emissions level.

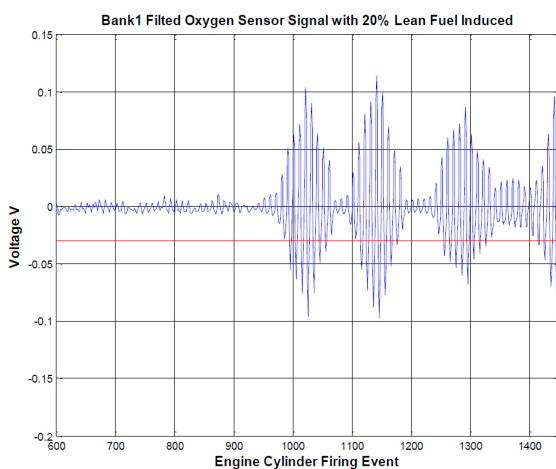


Figure 6. Filtered oxygen sensor voltages with Air-fuel ratio imbalance detection threshold

Figure 6 shows the filtered oxygen sensor voltage with air-fuel ratio imbalance detection threshold as a red line in Figure 6. If the filtered oxygen sensor voltage is below the air-fuel ratio imbalance detection threshold, a flag of *Air-fuel Ratio Imbalance Occurred* is set to True. It will be used to trigger the function 'Determine Rich/Lean imbalance status' to be executed at every engine cycle.

Calculating Filtered O2 Moving Average Buffer

This task is executed every engine cycle. The *Filtered Oxygen Sensor Voltage Buffer* is used to calculate the values of filtered O2 moving average buffer. There are five engine cycles buffered values to be used for the moving average calculation. At the end of each engine cycle, it takes one engine cycle of new buffered filtered O2 values, and four previous engine cycles data to calculate the mean values with the same buffer index. For a dual bank engine configuration, there are two Filtered O2 Moving Average Buffers. They are Bank1 and Bank2 Filtered O2 Moving Average Buffers.

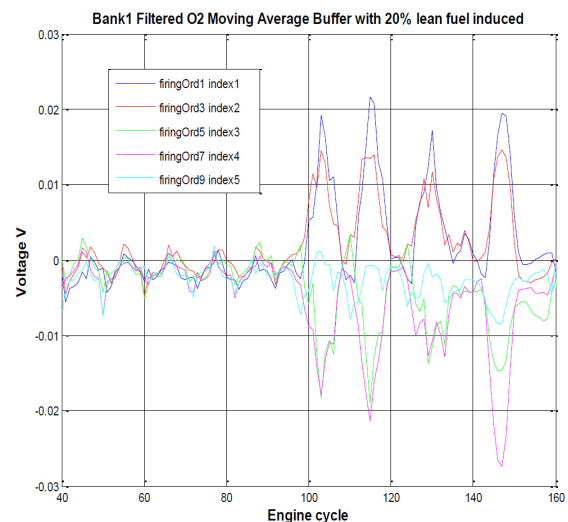


Figure 7. Bank1 Filtered O2 Moving Average Buffer with 20% lean fuel imbalance induced at cylinder1

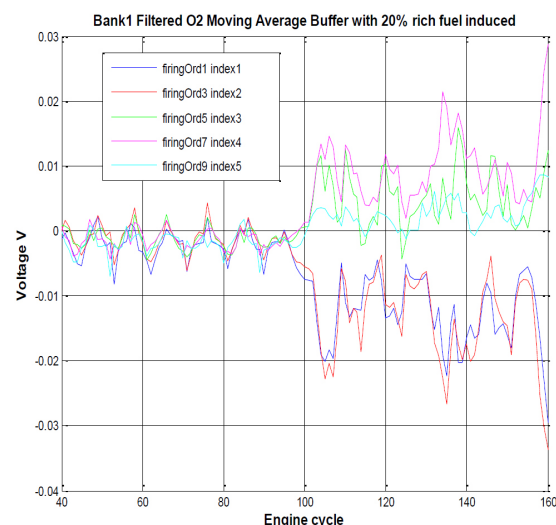


Figure 8. Bank1 Filtered O2 Moving Average Buffer with 20% rich fuel imbalance induced at cylinder1