

Diagnostics of Individual Air Fuel Ratio Cylinder Imbalance

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ABSTRACT

Air Fuel Ratio (AFR) imbalance between engine cylinders remains one of the most challenging problems in powertrain systems diagnostics. California Air Resources Board (CARB) has started imposing specific requirements on automotive companies since 2011 that required the integration of on-board diagnostics (OBD) monitor for the detection and reporting of this type of powertrain malfunction. In this paper, some methodologies of AFR cylinder imbalance monitoring are investigated and a novel approach is proposed that shows reliable detection capability compared to the other methods. The proposed method requires certain conditions during deceleration fuel shutoff events to intrusively reactivate the cylinders and determine the imbalance condition. The method was evaluated on a V6 3.7L engine in an experimental Lincoln MKZ vehicle. Vehicle results are shown and discussed.

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INTRODUCTION

AFR cylinder imbalance is an engine failure condition where the air-fuel ratio in one or more cylinders is different than the other cylinders due to a cylinder specific malfunction. This malfunction can be due to an intake manifold leak at a particular cylinder, fuel injector problem, an individual cylinder EGR runner flow delivery problem, an individual variable cam lift malfunction such that an individual cylinder is operating on the wrong cam lift profile, or other similar problems. Based on CARB regulations, an AFR cylinder imbalance monitor (AFCIM) is required for OBD to indicate failure of one or more cylinders when the fuel delivery system is unable to maintain the vehicles emissions at or below: 4.0 times the applicable FTP standards for PC/LDT SULEV II vehicles and 1.5 times the applicable FTP standards for all vehicles produced after 2014 ([3], [4]). One of the methods to detect the presence of individual AFR cylinder imbalance condition relies on the universal exhaust gas oxygen (UEGO) sensor measurement upstream of the catalyst. Many issues, however, are associated with this method, such as the sensor sensitivity to particular cylinders. This is mainly due to the geometry of the exhaust manifold and the position of the sensor in the exhaust manifold. Other monitoring methods rely on crankshaft acceleration estimation at particular commanded AFR to estimate the individual cylinder imbalance. The performance and robustness of this type of detection is problematic in the presence of random torque demand from accessories and in presence of many noise factors such as purge.

In [5], a method was proposed to detect an imbalance condition based on the frequency content of the measured UEGO sensor upstream of the catalyst. The magnitude of the frequency component of the signal was used to indicate whether the imbalance condition is present or not. This method is further applied to the measurement from the heated gas oxygen (HEGO) sensor downstream of the catalyst to

indicate whether the imbalance condition is lean or rich. In [6], a non intrusive diagnostics method was proposed that employed a post processing algorithm of the measured signal from a heated gas oxygen sensor placed upstream of the catalyst. The algorithm extracts the high frequency component of the sensor voltage to assess the balance condition during steady state conditions.

The AFR cylinder imbalance monitoring remains a challenging problem due to the fact that the monitor requires certain requirements and operating conditions in order to be able to use the oxygen sensor for the diagnostics. A typical engine bank will have two oxygen sensors, one upstream of the catalyst and one in the downstream position. These sensors are used to control the AFR being commanded to the engine cylinders to maintain stoichiometric operation while maximizing catalytic conversion efficiency and meeting emissions targets.

AFR controls is made in two closed loop control strategies. The inner AFR closed loop will control the commanded AFR to the cylinders to achieve an AFR target in the exhaust. This loop uses feedback from a UEGO sensor located upstream of the catalyst (S_1 in Fig.4) [7]. The AFR reference of this control loop is determined from the Outer closed loop that determines the appropriate lean or rich modulation based on the catalyst activity with the goal of achieving optimum catalyst efficiency. This control loop uses a HEGO sensor either located downstream of the catalyst (S_2 in Fig.4) in case of a full volume catalyst application or in the middle of the bricks of catalyst in case of a partial volume application. Both the UEGO and HEGO sensors are important to obtain accurate controls of the closed loop air fuel ratio control system and they must be located properly in order to sense evenly and accurately the AFR from each cylinder.

Sometimes, the geometry of the manifold or sensor locations can not be designed to meet ideal sensing and exhaust gas mixing due to vehicle design constraints and/or other engineering design requirements. When this is the case, the UEGO based approach for detection of AFR imbalance condition cannot be performed accurately/robustly. Fig.(1) shows the measured AFR from a UEGO sensor placed upstream of the catalyst. The data shown is obtained from an idle engine operation where a stoichiometric AFR is commanded and the injectors 1, 2 and 3 of this engine are sequentially disabled (one at a time), as shown in the bottom three graphs of Fig.(1).

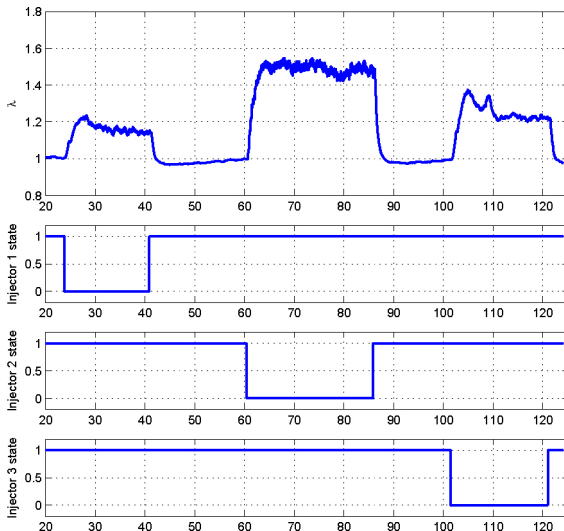


Figure 1. UEGO test data from a V6 3.7L engine

The data displayed in fig.(1) shows a difference between the measured AFR when only cylinder 1 is deactivated versus when only cylinder 2 deactivated versus when only cylinder 3 is deactivated. This simple experimental test shows an evidence that monitoring air fuel cylinder imbalance during this stoichiometric operation under similar operating conditions would not be enough to ensure robust estimation.

METHOD OF SOLUTION

During deceleration fuel shutoff (DFS) events, the combustion process is momentarily suspended until torque demand is reestablished. During this time (few seconds, generally), fuel delivery system will stop feeding the cylinders and then the UEGO sensor will measure lean conditions due to quasi total air mixture passing through the engine. The only possible fuel contribution during this time might be coming from the purge line as it may be releasing the fuel vapors being stored in the activated carbon canisters connected to the fuel tank. The process will start when the perfect steady state condition is established after the start of a DFSO event at which the UEGO measurement will settle at the lean plateau. A cylinder reactivation process will command an amount of fuel to each cylinder - one at a time from each bank, if more than one - and the the measured UEGO response is monitored for the amount of deviation/steady state reading. A system identification process is then employed to estimate the amount of fuel that is actually passing through the cylinder into the manifold and then to the sensor. Each UEGO deviation due to the commanded fuel to each cylinder will correspond to that specific cylinder and does not have to be exactly the

same for all cylinders. In fact, due to zone flow conditions, it is very likely that the sensor sensitivity to certain cylinders is different compared to other cylinders depending on the location of the sensor in the exhaust path.

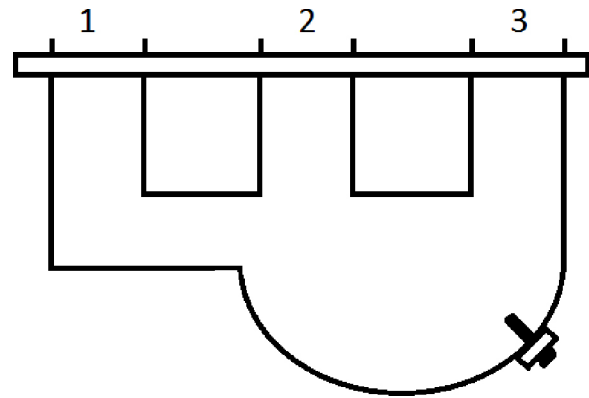


Figure 2. Illustration of an asymmetric UEGO position in a 3-cylinders manifold of a V6 engine

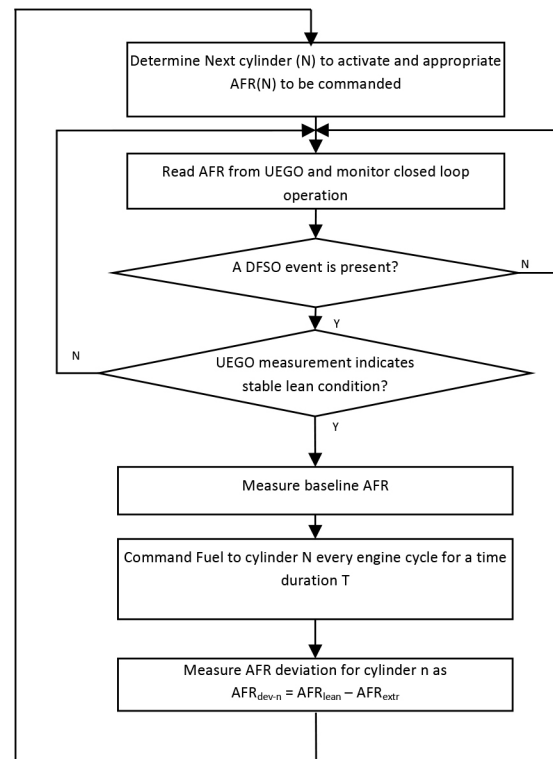


Figure 3. Reactivation process of cylinders during DFSO events

The reactivation process will sequentially command each cylinder separately for a duration of time that is enough to yield a steady state response of the UEGO sensor. The fuel/pulse modulation needs to be commanded at given entry conditions, such as engine speed and load for estimation consistency. The process may run for a given number of times and averaged results will be used to make a final determination if a fault is present. A basic approach is to map the amount of deviation into a magnitude of imbalance, either lean or rich imbalance based on the sign of relative difference (positive means higher deviation which indicates a rich AFR imbalance). A different approach is to calculate individual coefficients of imbalance