

Dynamic Misfire Threshold Determination Based On Zone-Level and Buffer-Level Adaptations for Internal Combustion Engines

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ABSTRACT

Misfire is generally defined as be no or partial combustion during the power stroke of internal combustion engine. Because a misfired engine will dramatically increase the exhaust emission and potentially cause permanent damage to the catalytic converters, California Air Resources Board (CARB), as well as most of other countries' on-board diagnostic regulations mandates the detection of misfire. Currently almost all the OEMs utilize crankshaft position sensors as the main input to their misfire detection algorithm. The detailed detection approaches vary among different manufacturers. For example, some chooses the crankshaft angular velocity calculated from the raw output of the crankshaft position sensor as the measurement to distinguish misfires from normal firing events, while others use crankshaft angular acceleration or the associated torque index derived from the crankshaft position sensor readings as the measurement of misfire detection. Regardless which measurement is chosen, an optimized threshold setting that clearly separates misfiring and normal firing cylinder events is desired. Traditionally, the threshold setting is determined during pre-launch calibration process with test data obtained from development vehicles. The threshold for each speed-load zone is typically a fixed value by looking up of a 3D calibration table. Such threshold setting approach, however, faces more and more challenges from the application of new engine technologies, because the crankshaft position sensor outputs could gradually change over the vehicle's life cycle, and could even change swiftly under stable engine speed and load conditions due to the application of certain new technologies. A fixed misfire threshold setting will yield false detections and result in regulation compliance concerns as well as unsatisfactory of the customers. To address this issue, this article propose a unique approach to dynamically determine the misfire threshold with zone-level adaptation to adjust thresholds for vehicle life-cycle changes and buffer-level adaption to address the needs to quickly adjust misfire thresholds in the same speed-load zone.

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INTRODUCTION

According to California Air Resources Board (CARB), "Engine Misfire" refers to lack of combustion in the cylinder due to absence of spark, poor fuel metering, poor combustion, or any other cause, and the combustion events in non-active cylinders due to default fuel shut-off or cylinder deactivation strategies are excluded [1]. Because the exhaust gas temperature will be dramatically increase by the unburned hydrocarbon from engine misfires, engine hardware, especially hardware in the exhaust system, will be potentially damaged. Therefore, the emission regulations worldwide mandate the detection of engine misfire and redeem it as a key on-board diagnostic (OBD) function [2].

To meet the stringent detection requirements on misfire, different approaches are developed. Some uses the instantaneous engine exhaust gas pressure [3]. Some other researches proposed to utilize the ionization signal in the combustion chamber [4, 5]. Some even developed the methods to use the model-based or sensor-based combustion chamber pressure to detect engine misfire [6]. Currently

the most common way that is used by almost all the OEMs is to utilize the crankshaft timing wheel and the associated crankshaft position sensor to obtain the angular velocity or acceleration of the engine crankshaft due to the low-hardware-cost and high-hardware-reliability advantages [7, 8, 9]. With the expectation of fluctuations in crankshaft angular velocity or acceleration caused by misfired cylinders, misfiring cylinder events are separated from normal firing cylinder events by applying different filters and various signal processing methods to the raw crankshaft position sensor outputs.

Although different OEMs take different approaches to separate misfiring cylinder events from the normal firing ones, all of these methods calculate an index (i.e., the misfire detection index) based on the crankshaft angular speed or acceleration, and require an optimized threshold setting for the calculated index that clearly identifies all the misfiring cylinder events with the detection rate that meets the regulation requirements. Two major approaches are adopted by OEMs to locate such a threshold for misfire detection: the after-processing approaches and the real-time processing methods [7, 11, 12, 13, 14, 15, 16].



The post processing approaches refer to the methods that rely on the data collection on development vehicles to calibrate and preset misfire thresholds for prescribed engine operating speed-load zones [7, 14, 15]. The misfire thresholds from the post processing method are fixed values for a specific engine operating speed-load zone such that the threshold values are lack of the ability to address the changes in crankshaft angular speed/acceleration that is NOT caused by misfire (for example, the vehicle-life cycle changes, the noisy signal from the sensors, the deterioration of sensors, and the application of new control algorithms / hardware).

The real-time processing methods are the ones that calculate or determine the misfire thresholds in real time, and have the capability to adjust the thresholds based on the past crankshaft position sensor outputs to achieve a better separation between the misfiring cylinder events from the normal firing ones [11]. Comparing with the post processing approaches, the real-time processing methods have the advantages of saving the engineering cost of post-processing calibrations, and adding the capability of addressing some of the changes in crankshaft angular speed/acceleration that is NOT caused by misfire. Therefore, the real-time processing methods are preferred by the industry. The studies and applications of real-time processing misfire threshold determination methods, however, fall far behind the development of misfire detection methods. The concept of real-time dynamic threshold for misfire detection was first proposed by Zhijian Wu and Anson Lee in 1999 [11], but its application is limited to the real-time processing methods with normalized misfire detection indices. It cannot handle the misfire detection index that varies from one speed-load zone to another, has challenges to normalize the detection index across speed-load zones and to determine a threshold when some of normal firing detection indices are mixed with misfiring detection indices, and has difficulties to balance long-term vehicle life-cycle changes and short-term index noises due to hardware or control algorithms. Masanobu Ohsaki and Hisanori Ozaki later proposed a mixed method utilizing the average correlation between the detection index and the calculated threshold. Their method first calculate a threshold based on said engine operating conditions, then calculate an average correlation between the diagnosis data and the threshold, and finally determine whether the misfire judgment is valid [13]. Although the usage of average correlation helps the reduction of false detection, their method cannot resolve the false detection issues caused by sensor deterioration, vehicle life-cycle change, and the sudden noise-level changes in the detection index caused by controls or hardware.

It is, therefore, desirable to have a dynamic threshold based on realtime crankshaft data processing that is not only able to gradually adjust the threshold settings with the vehicle lift cycle, but also capable to quickly adjust the threshold settings when there are sudden changes in the detection indices. The method proposed in this study meets the above needs by utilizing the zone-level adaptations to adjust for the long-term slow changes (such as the vehicle life-cycle changes), and the buffer-level adaptations to capture all short-term variations. In addition, the proposed method is independent of the normalization of the detection index because the division of speed-load zones is based on the characteristics of the associated detection

index (such as the mean value) and the specific crossing zone algorithm design ensures the smooth transition of thresholds in different zones.

This paper first introduces the fundamental principle to determine the misfire threshold. Then it investigates some popular misfire threshold determination methods, and points out their shortcomings. The dynamic misfire threshold determination method that is based on zone-level and buffer-level adaptations is finally introduced in detail with simulation results to demonstrate the advantages of this method. Summaries and conclusion are at the end.

FUNDAMENTAL PRINCIPLE TO DETERMINE MISFIRE THRESHOLD POPULAR AND DESIGN FOR SIX SIGMA

Regardless which method is used for misfire threshold determination, the fundamental principle of threshold determination should be followed. That is, the threshold should clearly separate normal firing and misfiring events and minimize the false detection ratio. Regulations, such as CARB [1], have very strict requirements on the detection ratio for misfire.

Figure 1 demonstrated an example of the distribution of misfire detection index for a four- cylinder engine. The normal firing detection indices are distributed in a band shape, and so are the misfiring detection indices. This naturally allows the application of the principles of design for six sigma (DFSS) [17] to minimize the false detection ratio.

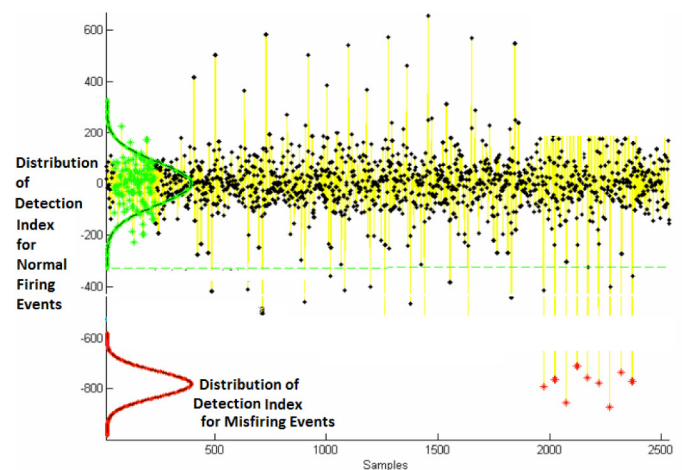


Figure 1. An example of misfire threshold determination for after-processing methods. Note: the vertical axis represents the values for detection indices, and the horizontal axis represents the probability of the detection indices to be close to a certain value.

In most of the engine operating conditions, the detection index follows the above distribution shape. This allows an easy application of DFSS principles to the setting of thresholds. If the threshold is set anywhere inside the shaded area in Figure 2, the detection ratio for misfire will be at least 99.99966%, and such threshold setting will satisfy any regulation requirements in the world. Most OEMs follow the DSFF principles to determine the misfire threshold.

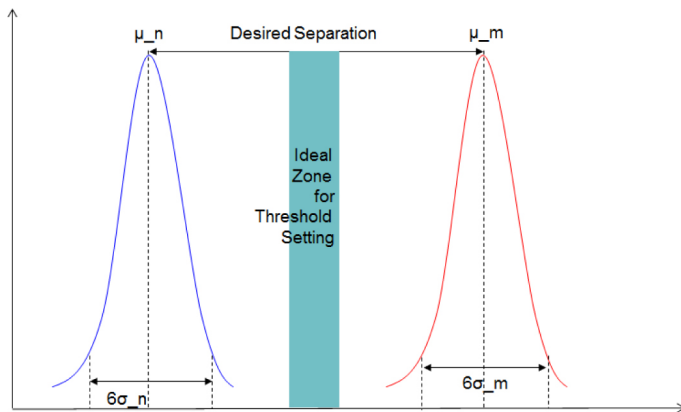


Figure 2. Desire zone for misfire threshold settings where μ_n is the mean of normal firing events, $6\sigma_n$ indicates the six sigma zone for normal firing events, μ_m is the mean of misfiring events, and $6\sigma_m$ indicates the six sigma zone for misfiring events. Note: the horizontal axis represents the values for detection indices, and the vertical axis represents the probability of the detection indices to be close to a certain value (or the number of detection index samples per unit detection index zone).

MISFIRE THRESHOLD DETERMINATION METHODS AND THEIR SHORTCOMINGS

As mentioned in the introduction section, all the misfire threshold determination methods fall into two categories: post processing and real-time processing.

Post Processing Methods

All post processing methods are similar. They rely on the data collected from the development vehicles, post-processing of the data yields the zone division, the worse cases of normal firing and misfiring events, the associated distributions, and the best areas to set thresholds. For example, if Figure 1 is the test data collected from a development vehicle in the zone of engine speed [1000 RPM , 1500 RPM] and load [10%, 15%]. For that specific zone, the threshold could be set inside the blue band as show in Figure 3.

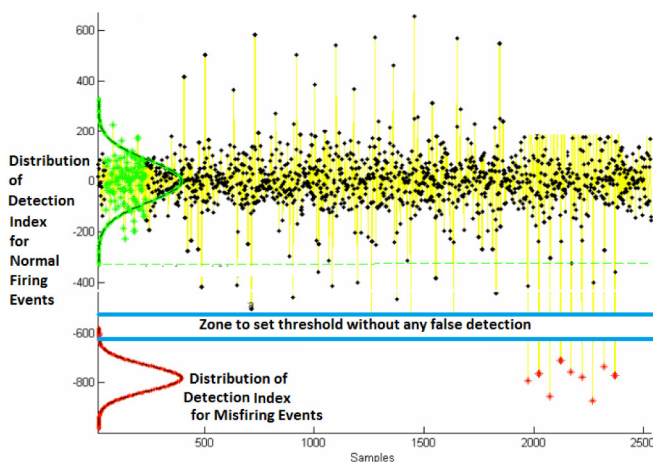


Figure 3. An example for misfire threshold determination for post-processing methods. Note: the vertical axis represents the values for detection indices, and the horizontal axis represents the probability of the detection indices to be close to a certain value

The post processing methods work well for vehicles has little changes in detection indices over its life cycle, as long as the worse cases are considered during the post-processing calibration process. Once the threshold is set, it is generally fixed (there could be some fine-tuning on the threshold for specific operating conditions by multiplying a coefficient to the threshold or adding/subtracting a factor). Thus, if the distribution changes in that zone (for example, due to crankshaft sensor deterioration), false detection will happen. This is the biggest shortcoming for all post-processing methods.

For example, Figure 4 illustrates one such case of false detections. The distributions of normal firing and misfire detection indices (in solid blue and red lines) are shifted to the dashed blue and red lines. The original ideal zone for setting the misfire threshold is no longer safe, because there will be high probability for normal firing cylinder events to be falsely detected as misfiring cylinder events if the threshold remain the same in the shaded zone in blue color.

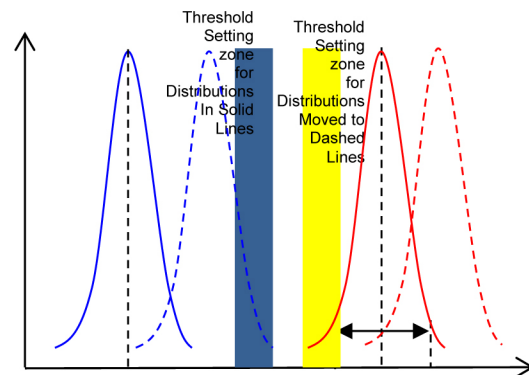


Figure 4. An example of false detections due to shifted distributions of detection indices where the blue curves represent the normal firing distribution and the red curves represent the misfiring distribution (solid curve- original distribution, dashed curve- shifted distribution). Note: the horizontal axis represents the values for detection indices, and the vertical axis represents the probability of the detection indices to be close to a certain value

Another disadvantage for post processing methods is that the test data used to develop the misfire threshold is typically collected from development vehicles. The sample size is usually small. Even if the worst cases are considered by the calibration engineers, false detection could happen due to the non- representative test data from the small sample of test vehicles. To improve the detection ratio and the robustness of threshold settings, the calibration engineers usually are required to perform several cycles of data collection – data analysis – threshold adjustments. This involves huge engineering efforts and costs.

Real-Time Processing Methods

Real-time processing methods refer to the methods that could actively adjust misfire threshold based on the real-time data. They usually have the capability to lean the past detection indices, and use the learned information to adjust the threshold for the future misfire detections. To actively adjust the threshold setting to the best zone that separates normal firing and misfiring events is the biggest advantage for real-time processing methods. For example, in Figure 4, if a real-time processing