A new concept of misfire detection using a wide-range oxygen sensor in a spark-ignition engine

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Abstract: Misfiring in spark-ignition engines can cause immediate damage to the catalyst and increase emissions since it brings unburned fuel and oxygen into the catalyst, resulting in an increase in temperature owing to subsequent combustion. Therefore, misfiring must be detected, as specified in the on-board diagnostics (OBD) regulations. One of the common methods of misfire detection is to detect the fluctuation in angular velocity of the crankshaft, which can be misdetected under conditions of high speed and low load and under conditions of rough road driving. An alternative method of misfire detection is suggested here, which utilizes the signal fluctuation of a wide-range oxygen sensor installed at the confluence point in the exhaust manifold. To understand the fluctuation in the wide-range oxygen sensor signal caused by a misfiring, the fluctuation in oxygen concentration in an exhaust manifold was estimated by measuring the hydrocarbon concentration. The effect of the transient response of a wide-range oxygen sensor on misfire detection performance was also investigated. It was found that differentiation of the sensor signal gives the criteria for misfire detection. The misfiring can be detected by monitoring the amplitude of the fluctuation in the differentiated signal, and the misfired cylinder can be identified by monitoring the phase delay between the peak point of the differentiated signal and a reference signal. This scheme has been shown to detect the misfiring condition reliably and to identify the misfiring cylinder up to an engine speed of 5000 r/min.

Keywords: on-board diagnostics, misfire, hydrocarbon emission, wide-range oxygen sensor, misfired gas, monitoring parameter, misfire detection

NOTATION

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>CCC</td>
<td>close-coupled catalyst</td>
</tr>
<tr>
<td>ECU</td>
<td>engine control unit</td>
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<tr>
<td>f(t)</td>
<td>exciting function</td>
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<tr>
<td>g(t)</td>
<td>indicial response</td>
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<tr>
<td>h(t)</td>
<td>impulse response</td>
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<tr>
<td>HC</td>
<td>Hydrocarbon</td>
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<tr>
<td>OBD</td>
<td>on-board diagnostics</td>
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<tr>
<td>t</td>
<td>time</td>
</tr>
<tr>
<td>x(t)</td>
<td>response at time t</td>
</tr>
<tr>
<td>x</td>
<td>given crank angle between 0 and θ</td>
</tr>
<tr>
<td>δ(t)</td>
<td>unit impulse</td>
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1 INTRODUCTION

When a vehicle with a spark-ignition engine has aged and not been repaired properly, many kinds of problem can be found in the ignition and fuel injection systems. In particular, when the ignition system has problems such as a wide spark plug electrode gap, a loose contact of the spark plug cable or contamination in the distributor, the fuel and air mixture brought into the cylinder occasionally fails to burn and a significant amount of unburned hydrocarbon (HC) is exhausted into the atmosphere. Therefore, even a small rate of misfiring leads to an increase in the hydrocarbon emission by a factor of up to 1.5 compared with the emission standard. Misfiring can also cause immediate damage to the catalyst since unburned fuel and oxygen brought into...
the catalyst will lead to a subsequent combustion resulting in a temperature increase. In 1993, the California Air Resources Board (CARB) decided to impose the enhanced on-board diagnostics (OBD-II) regulation to automobiles powered by spark-ignition engines. The US Environmental Protection Agency (EPA) also adopted this regulation from the 1996 model year vehicles. In this regulation, the detection of misfiring is one of the most important factors in view of the heavy impact of misfiring on emission. According to the CARB OBD-II regulation [1], the diagnostic system is to monitor engine misfire and to identify the specific cylinder experiencing the misfire. Regarding the engine operating range for misfire detection, the regulation requires misfiring to be monitored during all positive torque operating conditions. However, as an exception, manufacturers may disable misfire monitoring in the operating range of high speed with low engine load conditions.

Many kinds of strategy to detect misfiring have been proposed and can be grouped into three categories. The first method is to detect the fluctuation in angular speed of the crankshaft, which was introduced by Klenk et al. [2] and Ribbens and Rizzoni [3]. The engine control unit (ECU) monitors the fluctuation in crankshaft angular speed through the crankshaft position sensor with a toothed sensor wheel. Car manufacturers have favoured this method because it does not need an additional sensor and requires software modification only. However, as noted by Klenk et al. [2], this method also needs an additional vehicle gravitational acceleration sensor to prevent misdetection under rough road driving conditions. This method is also known to have a serious shortfall in its application range, especially at high engine speeds with low loads. The second method is to monitor in-cylinder combustion behaviour, which was proposed by Herden and Kussel [4], Ohashi et al. [5] and Shimasaki et al. [6]. In this method, the misfiring is detected by monitoring the voltage waveform of a spark plug or the ion current between the electrodes of a spark plug. The cylinder pressure is also used to monitor in-cylinder behaviour. This method is very accurate in detecting misfire since the behaviour in the cylinder is monitored directly. However, this has not been adopted by car manufacturers since it has the inherent disadvantage of needing an additional sensor or power supply. The third method is to monitor the pressure or oxygen concentration in the exhaust system. The pressure in the exhaust manifold usually fluctuates periodically and decreases abnormally when a misfiring has occurred in a cylinder. This deviation in the pressure from the normal pattern of exhaust pressure gives information about the faulty combustion. This method also has an economic disadvantage in that it needs a special pressure sensor for the detection of misfiring. Monitoring the oxygen concentration using a conventional oxygen sensor, which was proposed by Bozek et al. [7], is advantageous in that it does not need an additional sensor since a sensor is already used for lambda feedback control. However, this method cannot detect misfire in lean operating conditions because of the non-linear switching characteristics of a conventional oxygen sensor.

Wide-range oxygen sensors recently introduced by Hitachi (1986), NTK (1992) and BOSCH generate output voltage according to the oxygen concentration and air–fuel ratio. The transient response characteristics have also been improved. Yamada et al. [8] proposed a possibility of using a wide-range oxygen sensor for misfire monitoring. However, the monitoring method has not been investigated seriously because of its slow dynamic response characteristics (the response time was about 300 ms). BOSCH’s wide-range oxygen sensor LSU has fast dynamic response characteristics because its sensing element is planar, so that its typical response time is 30–100 ms. Wide-range oxygen sensors are still expensive to use in production vehicles compared with conventional oxygen sensors. However, the price of a wide-range oxygen sensor is expected to come down to the level of a conventional oxygen sensor since the use of wide-range oxygen sensors is likely to expand to meet the enhanced emission standards. Hasegawa et al. [9] and Nasu et al. [10] used wide-range oxygen sensors for lambda feedback control of individual cylinders and for a model-based fuel injection control respectively.

Location of the oxygen sensor is important in that it reflects the state of the exhaust gases. If the sensor is installed too far downstream in the exhaust pipe, it could not be used for misfire detection since the mixing of exhaust gas attenuates any fluctuation in oxygen concentration. As the location of both the catalyst and the oxygen sensor is moving closer to the engine exhaust manifold to fulfill the latest emission standards, the fluctuation in the oxygen concentration at the position of the oxygen sensor is more pronounced than that further downstream.

In this paper, a new method of misfire detection is proposed. Fluctuation in the oxygen concentration at the confluence point of the exhaust manifold is monitored using a wide-range oxygen sensor with relatively fast dynamic response characteristics. Hydrocarbon and oxygen concentrations caused by a misfiring were investigated to understand the response of the wide-range oxygen sensor. The signal from the wide-range oxygen sensor was also investigated to see whether the sensor could reflect the gas concentration fluctuation caused by a misfiring and thus be used for misfire monitoring.
2 FLUCTUATIONS IN HYDROCARBON AND OXYGEN CONCENTRATIONS BECAUSE OF A MISFIRING

The output voltage of a wide-range oxygen sensor changes with the oxygen concentration in the exhaust manifold. To understand the response characteristics of a wide-range oxygen sensor to an ignition-induced misfiring, the oxygen concentration fluctuation in the exhaust manifold was interpreted by measuring the hydrocarbon concentration. The fluctuation in oxygen concentration caused by the misfired gas could be estimated by measuring the hydrocarbon concentration, since the ratio of the hydrocarbon concentration to the oxygen concentration was maintained when the misfired gas passed through the exhaust manifold. Flow characteristics of the misfired gas in the exhaust manifold were also investigated through measurements of the hydrocarbon concentration.

2.1 Experimental equipment

A fast-response hydrocarbon analyser, HFR 400 by Cambustion, was used to investigate the fluctuation in hydrocarbon concentration in the exhaust manifold. The analyser responds very quickly to the change in hydrocarbon concentration. As reported by Collings et al. [11], the rise time for a step change in hydrocarbon is 4 ms and the delay time is approximately 10 ms. The response time of the analyser was neglected in this study, since the rise time of this analyser is much faster than the rise time of the wide-range oxygen sensor, which is about 30–100 ms. The results of the hydrocarbon analyser were advanced 10 ms to compensate for the delay time. The experimental set-up is shown in Fig. 1. Sensing probe locations were selected to be at three different points: at 30 and 150 mm from the joint between the cylinder head and exhaust manifold of cylinder 4, and at the confluence point as shown in Fig. 2a. Misfire was induced by a misfire generator which interrupted the ignition signal from the engine control unit (ECU) to the ignition coils. The misfire generator, made by BOSCH, could interrupt the ignition signal for a given interval for each cylinder. The signal from the fast-response hydrocarbon analysers was recorded along with the phase sensor (camshaft position sensor) signal and the misfire trigger signal through a data acquisition system with 1° crank angle (CA) resolution. The phase sensor signal generated one pulse per cycle and was used as a reference signal of crank angle since its falling edge is fixed at 129°CA before top dead centre (TDC) of the compression stroke of cylinder 1 (or TDC of the intake stroke of cylinder 4).

2.2 Hydrocarbon concentration at the confluence point of the exhaust manifold

A typical gaseous hydrocarbon concentration at the three measuring points in the exhaust manifold is shown in Fig. 2b. A single misfire was triggered by interrupting the ignition signal for cylinder 4 during normal engine operation. The shapes of the hydrocarbon concentration fluctuations at 30 and 150 mm positions were similar, but were apparently different from that at the confluence point. The shape at the confluence point had twin peaks. This can be explained by the fact that the manifold configuration inevitably allows mixing of the misfired gas with the fired gas from the other firing cylinders. The characteristics of the twin peaks of hydrocarbon concentration at the confluence point can be interpreted by considering the flow and mixing characteristics of the misfired gas in the exhaust.
Fig. 3 Mixing characteristics of misfired gas in the exhaust manifold

carbon concentration should be detected at the confluence point during $N + 1$ cycles, since two peaks are detected during two cycles for one misfiring.

2.3 Effects of engine load and speed on the flow of misfired gas

To investigate the effect of engine load on the characteristics of misfired gas flow, variations in hydrocarbon concentration at the confluence point were compared as engine load increased from a quarter to full load. The characteristics of the twin peaks pattern were maintained for the entire load range as shown in Fig. 4a. The first peak in hydrocarbon concentration became even stronger while the second peak became weaker under higher engine load conditions. This is because the mass flowrate of the misfired gas increases as the engine load increases. The effects of engine speed under no-load and half-load conditions were compared (Figs 4b and c). The variation in hydrocarbon concentration of misfired gas was not delayed with engine speed irrespective of engine load, since the speed of the exhaust gas also increased at the same rate as the increase in engine speed.

3 DETECTION OF OXYGEN CONCENTRATION USING A WIDE-RANGE OXYGEN SENSOR

3.1 Signal variation of a wide-range oxygen sensor caused by an ignition-induced misfiring

In this study, a wide-range oxygen sensor (LSU, by BOSCH) and its controller (AWS, by ETAS) were used. The sensitivity of the sensor to lean mixtures is different from that for rich mixtures. However, within...
each range of rich or lean mixtures, the output signal is still well correlated with and nearly proportional to the air–fuel ratio, and the relationship of the sensor output voltage to the oxygen concentration is linear. The dynamic characteristics of the oxygen sensor are represented by the time constant, $t_{0,3}$, which is the time taken for the output signal to reach 63 per cent of the steady state output voltage. The time constant of the LSU sensor is reported to be 30–100 ms, which is much slower than the maximum rate of change in the hydrocarbon concentration caused by the flow of misfired gas. This problem has been carefully considered during this study. As mentioned above, when an ignition-induced misfire is triggered in a specified cylinder, the oxygen and hydrocarbon concentrations at the confluence point in the exhaust manifold fluctuate in a pattern that has twin peaks during two cycles. These fluctuations in the hydrocarbon and oxygen concentrations function as the input to the wide-range oxygen sensor. The output signal of the wide-range oxygen sensor fluctuates with the same pattern as the fluctuation in hydrocarbon concentration. However, since the response speed of the sensor is slower than the speed of the fluctuation in hydrocarbon and oxygen concentrations, the output signal is attenuated and delayed as shown in Fig. 5.

### 3.2 Differentiation of the sensor signal for reliable detection of misfiring

Theoretically, attenuation is likely to be a serious problem at high engine speeds, since the amplitude of the output signal decreases as input frequency increases under high-speed conditions. The frequency of the input signal fluctuation increases with engine speed, in a time base, even though it does not increase with engine speed, in a crank angle base, as shown in Fig. 4b. Consequently, the amplitude of the sensor output signal is expected to be attenuated as the engine speed increases, if the response characteristics of the sensor do not change with engine speed. To distinguish a misfiring from normal combustion even under high-speed conditions and to overcome the problem of signal attenuation under high-speed conditions, differentiation of the sensor signal was tried. As shown in Fig. 6, the fluctuations in a differentiated signal caused by misfiring were more noticeable than the variations in the raw signal, so that the differentiated signal could be used as a monitoring signal for the detection of misfires using a wide-range oxygen sensor. The raw signal of a wide-range oxygen sensor was smoothed and
differentiated with a 1°CA interval. If the signal was not differentiated and the voltage level of the raw sensor signal was used for misfire detection, misdetections could occur occasionally when the engine was operated under lean conditions, since the increase in the sensor output voltage caused by a misfiring could not be distinguished from that from normal lean combustion.

4 EFFECT OF THE DYNAMIC CHARACTERISTICS OF A WIDE-RANGE OXYGEN SENSOR

The behaviour of a random input signal can be investigated by looking at the transient response characteristics of the system to a unit step input. It is useful to consider a system with an initial response \( g(t) \) which is the response of a system to a unit step function applied at \( t = 0 \). At a given time \( \tau \), the exciting function has the value \( f(\tau) \), and there is an increase in the amplitude \( \Delta f(\tau) \), corresponding to a time increment \( \Delta \tau \). The contribution to the response of a step function with an amplitude \( \Delta f(\tau) \) applied approximately at \( t = \tau \) is

\[
\Delta x(t, \tau) \approx \Delta f(\tau) g(t - \tau)
\]

If \( f(0) \) is the amplitude of a step function applied at \( t = 0 \) and \( \Delta \tau \to 0 \), the response at any time \( t \) is given by

\[
x(t) = f(0) g(t) + \int_0^t \frac{df(\tau)}{d\tau} g(t - \tau) \, d\tau
\]

and it can be reduced to a convolution integral form as follows:

\[
x(t) = \int_0^t f(t - \tau) h(\tau) \, d\tau \quad \text{or} \quad \int_0^t f(\tau) h(t - \tau) \, d\tau
\]

where

\[
h(t) = \frac{dg(t)}{dt} + g(0) \delta(t)
\]

and

\[
h(t) = \frac{dg(t)}{dt}
\]

when \( g(0) = 0 \).

In the crank angle base, equation (3) can be interpreted as

\[
x(\theta) = \int_0^\theta f(\theta - z) h(\theta - z) \, dz \quad \text{or} \quad \int_0^\theta f(z) h(\theta - z) \, dz
\]

where \( \theta \) and \( z \) are the crank angles from a reference point.

The response to a random input could be predicted if information about its indicial response were available. To obtain information about the characteristics of the indicial response of a wide-range oxygen sensor, especially under misfiring conditions, a test on a real engine was carried out. A wide-range oxygen sensor was installed at the entrance of its exhaust manifold. The sensor signal was taken when a single misfiring was triggered. The test was carried out for different engine speeds, from idle to 4000 r/min, under no-load conditions. In this case, the step change in hydrocarbon concentration initiated a step input to the sensor as shown in Fig. 7a. The responses to the step input at different engine speeds were compared as shown in Figs 7b and c. If the responses were compared in a time base, the response time decreased with engine speed, whereas if compared in a crank angle base, there was no significant change in the response characteristics with engine speed. However, there was some delay angle to the increase in sensor voltage at high engine speed conditions. This was also shown in the test results carried out by Wiedemann et al. [12] and by Mizusawa et al. [13], where it was recognized that the transient response of a wide-range oxygen sensor was considerably influenced by the gas flow rate and temperature. The response rate increased with engine speed in a time base, because both the gas flow rate and temperature increased with engine speed. From the results concerning the transient response of the sensor, it could be concluded that the transient response of a wide-range oxygen sensor was fast enough to detect engine misfiring even under high engine speed conditions. If the response time were not influenced by gas flowrate and temperature, the amplitude of the fluctuations in the differentiated signal would decrease, like the dashed

![Fig. 6 Comparison between (a) a raw sensor signal and (b) a differentiated signal](image-url)
5 EFFECT OF ENGINE OPERATING CONDITIONS ON THE PATTERN OF SENSOR SIGNAL FLUCTUATION

The waveforms of the differentiated signal fluctuation were compared as the engine load increased from a quarter to full load, as shown in Fig. 9. The comparison was conducted at 2000 r/min, interrupting the ignition signal to cylinder 4. The basic pattern of twin peaks for one misfiring was maintained as the engine load changed, but the amplitude of the first peak increased with engine load, as shown in Fig. 9a. This is mainly caused by the increase in the first peak of the hydrocarbon or oxygen concentration with engine load, as shown in Fig. 4. The increase in the sensor response...
(a) Effect of engine load on the fluctuation of differentiated signal and its amplitude of the first peak

(b) Effect of engine load on the phase delay between the reference signal and the second peak of differentiated signal

Fig. 9 Effects of engine load (a) on the fluctuation in the differentiated signal (2000 r/min, cylinder 4 misfiring) and its peak amplitude and (b) on the phase delay between the reference signal and the second peak of the differentiated signal

rate also affected the increase in the amplitude of the differentiated signal since the increased flowrate of the exhaust gas increased the response rate of the sensor. The phase delay of the differentiated signal from the reference was also compared as engine load increased. As expected in our previous modeling study of the exhaust gas flow characteristic, the phase delay angle of the differentiated signal decreased with engine load, as shown in Fig. 9b, because the gas flowrate increased with engine load. The phase delay is the angle from the reference to the second peak of the differentiated signal. The deviation in the cyclic variation in phase delay under constant conditions became smaller at higher engine loads, as shown in Fig. 9b.

The effect of the engine speed on the differentiated signal is shown in Fig. 10. The basic pattern did not change with engine speed. This is because the fluctuations in the gas concentrations shown in Figs 4b and c are not affected by the engine speed, and the transient response characteristics of the sensor are also unaffected by engine speed, as shown in Fig. 7c. The amplitude of the fluctuations in the differentiated signal decreased at the 5000 r/min no-load condition. However, the fluctuating amplitude is still significant
compared with the amplitude under normal combustion conditions and the misfiring could be detected by monitoring the differentiated signal, even at the 5000 r/min no-load condition. The phase delay of the fluctuation in the differentiated signal was also compared with increase in the engine speed under no-load conditions and with the triggering of misfires for each cylinder, as shown in Fig. 10b. The phase delay increases with engine speed, because there is some increase in delay angle in the sensor response at high engine speed conditions as shown in Fig. 7c. The effect of engine speed on phase delay was also investigated under half-load and no-load conditions, as shown in Fig. 10c. The phase delay also increases with engine speed under half-load conditions, as under no-load conditions. The identification of the misfiring cylinder was reliable even under high-speed conditions as shown in Fig. 10b, since there is

(a) Effect of engine speed on the fluctuation of differentiated signal and its amplitude (No load, #1 cylinder misfiring, 1 misfire / 10 cycles)

(b) Effect of engine speed on the phase delay between the reference signal and the second peak of differentiated signal (under no-load condition changing the misfiring cylinders)

(c) Effect of engine speed on the phase delay between the reference signal and the second peak of differentiated signal (under 1/2-load and no-load conditions misfiring #4 cylinder)

Fig. 10 Effects of engine speed (a) on the fluctuation in the differentiated signal and its amplitude (no-load, cylinder 1 misfiring, 1 misfire/10 cycles), (b) on the phase delay between the reference signal and the second peak of the differentiated signal (under no-load condition with change in the misfiring cylinder) and (c) on the phase delay between the reference signal and the second peak of the differentiated signal (under half-load and no-load conditions, cylinder 4 misfiring)
sufficient margin between the phase delay angles even when the cyclic variation in the delay angle of 30–40 samples for each neighbouring cylinder is taken into account. Therefore, it was concluded that the phase delay could be used for identification of the misfiring cylinder.

6 CONCLUSIONS

A new concept of misfire monitoring has been presented. A wide-range oxygen sensor, installed at the exhaust confluence point, can provide sufficient information for misfire detection. The concept was validated with engine tests under various load and speed conditions, and also by cross-checking the exhaust gas concentration measurements with the flow model. The major conclusions are:

1. The measurement of the hydrocarbon concentration caused by a single misfiring at the exhaust manifold confluence point shows twin peaks throughout the entire range of engine operating conditions.
2. The existence of these concentration peaks correlates with misfire in the cylinder. The concentration measurement was attenuated and delayed when a commercially available wide-range oxygen sensor was used to detect the change in gas composition because of the transient response of the sensor. To identify the misfire, the sensor signal must be appropriately processed.
3. In order to distinguish a misfiring from normal combustion, it is preferable to differentiate the sensor signal. The misfiring can be detected by monitoring the amplitude of the fluctuation in the differentiated signal, and the misfired cylinder can be identified by monitoring the phase delay between the peak point of the differentiated signal and a reference signal.
4. The fluctuation amplitude of the differentiated signal increases with engine load and decreases with engine speed. The phase delay angle from the reference signal decreases with engine load and increases slightly with engine speed.
5. The transient response rate of a wide-range oxygen sensor increases with engine speed. The transient response of the sensor was found to be fast enough to detect the fluctuations in oxygen concentration caused by a misfiring, even under high-speed conditions.

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