Types of Signal Pre-Processing Approaches for Engine Misfire Detection (EMD) Algorithm

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Abstract: With the advent of recent environmental issues, misfire detection systems are becoming increasingly important in automotive market. An early misfire diagnosis also allows to prevent damages to the exhaust emission system and consequent costs for the user. Today few low cost methods exists in order to precisely detect single misfires in real time, the majority in fact require the use of expensive sensors (e.g. pressure sensors) or dedicated circuits (e.g. ionization current sensing). This work describes some relevant procedures capable of detecting misfires with good accuracy. The proposed method is exclusively based on the real time analysis of the crankshaft angular velocity and its variations. This is possible since each misfire event generates an abrupt perturbation of the crankshaft angular velocity that can be detected using an appropriate signal processing algorithm.

Keywords: Misfire detection, Exhaust emission, Automotive, Crankshaft angular velocity, Signal processing algorithm.

1. BACKGROUND

Internal combustion engine uses fuel and air for its combustion to exert kinetic energy in vehicles. Thus, it has a tendency to generate misfire during the combustion stroke of an engine. Misfire could be defined as the mixture of fuel and air that is not igniting as it should inside the combustion chamber that contributes to loss of engine power or failure (Naik, 2004). The causes of misfire could be spark plug faulty, leaky ignition coil wire insulator, leaky intake manifold, mechanical damage to the engine, injector faulty, and improper ignition timing (Merkisz et al., 2001). Besides air pollution, this type of defection is dangerous in vehicle handling system and increases the risk of engine fatigue and accident. Since the standard and regulations are implemented for on board diagnostic system, there are various methods of engine misfire detection (EMD) by using different sensors and algorithms for signal processing.

Moreover, based on previous studies and research development, crankshaft position sensor (CPS) has been commonly used to acquire instantaneous crankshaft angular velocity due to its magnetic effect by the tooth of flywheel, as shown in Fig. 1.

Fig. 1. Crankshaft Position Sensor Placement

Fig. 2. Misfire detection technique flowchart
However, the signal processing algorithms are varied. Basically, the pulses of CPS are acquired and they measure the period between one pulse and another. Therefore, it is defined as reference period for misfire identification. In order to identify misfire, the engine speed will instantaneously drop. Some simple techniques for misfire detection measure the difference between two consecutive reference periods and misfire is considered when the differences rise to their threshold. However, there are noises from the engine parameters signal and they can affect time varying disturbances that will decrease the efficiency of EMD. The process of advanced signal processing can compensate the noises and disturbances to increase accuracy. Fig. 2 shows the steps of the processing where signal acquisition, measurement, noise reduction, and identification had been conducted (Naik, 2014).

2. NOISE REMOVAL USING BIQUADRATIC NOTCH FILTER

It is worth to be noted that, noise can be developed from combined engine speed signature due to cylinder torque imbalance, crankshaft torsional vibrations, and irregular crankshaft trigger wheel geometry. For feature extraction purpose for removing such noises developed caused by intermittent misfire, biquadratic notch filter in (1) was used as the basic building block of the proposed digital filter array where \( m \) is an integer multiple of the engine cycle frequency, \( \rho \) is the radial location of the poles in the z-plane, \( b_m \) is a constant gain, and \( f_s \) is the number of samples per engine cycle (Proakis and Manolakis, 1996).

\[
H_m(z) = \frac{b_m}{z^2 - 2 \cos(2\pi mf_s)z + 1}
\]

The notch filter is then used as a component of the filter for intermittent misfire residual generation, refer to (2) and continuous misfire (3). Furthermore, there are varied filters due to different noise generation at different conditions of misfire. Nonetheless, output of \( T(z) \) and the change detection approach for intermittent misfire will not detect this condition at a steady-state, where continuous misfire information exists.

\[
D(z) = 1 - \prod_{m=0}^{m} H_m(z)
\]

3. MISFIRE DIAGNOSIS USING SNR

In high speed and low load engine conditions, there is preprocessing on combustion time interval by increasing signal to noise ratio (SNR) to increase misfire diagnosis efficiency.
Noise amplitudes with similar amplitude to misfire give signal in the combustion time signal before the signal filtering process begins. Increasing SNR produces contrary amplitude between noises and misfires signal. Moreover, the averaging process is used to extract the features of the signal. Fig. 4. shows the signal of combustion interval, which is acquired by using CPS and its moving average without misfire actuation where the process obtains more uniform combustion time signal and reduces the noise caused by systematic cylinder-to-cylinder different combustion behaviours (Cavina et al., 2006).

4. LU MISFIRE INDEX

After signal pre-processing to overcome noises of the signal, EMD algorithm takes place for misfire recognition. There are many algorithms and approaches for this purpose. Based on a previous research, the well-known LU misfire index is used (4), where $T_i$ and $T_{i-1}$ are two consecutive combustion time intervals (Klenk et al., 1993).

$$LU_i = \frac{T_i - T_{i-1}}{T_{i-1}}$$

(4)

![Fig. 5. Before Pre-Processing](image1)

![Fig. 6. After Pre-Processing](image2)

By using LU misfire index, real time or online EMD could be done due to its simple algorithm and less computational speed. Besides, there is a threshold value for the index comparison between misfire and normal combustion index. Misfire is detected when the current LU value is more than the threshold value. Fig. 5 and Fig. 6 show the detection of misfires by using LU misfire index before and after signal pre-processing by using moving average of CPS signal.

Moreover, engine torque estimation based on CPS signal is generated without using load cell. The analysis of torque signal generation contributes to EMD as well since misfire decreases the torque of an engine. Moreover, the Parametric Kalman Filter is used to estimate the torque based on CPS signal (Jakubek and Fleck, 2009). This has been continued for EMD by using interacting multiple model (IMM) (Helm et al., 2012). The advantages of this method are a phase free estimation, excellent in noise reduction, and high robustness against parameterization errors.

5. RESIDUAL EVALUATION USING MARKOV CHAIN

The residual generation would be used for EMD by using residual evaluation method that is carried out by using Markov chain. The method has been proven in a study on statistical properties of air intake in the cylinder since engine power is manipulated by controlling the amount of air intake. It was conducted to ensure that the fluctuations of crankshaft speed are indeed Gaussian and Markov (Mehdi et al., 2011). Better accuracy with less false alarm rate had been the result obtained from the residual analysis using limiting probability of Markov chain. Furthermore, the application of Markov chain has been used for fault diagnosis as well (Morgan and Liu, 2009).

Other than that, a study on how misfire is developed is important to evaluate the effect of misfire on energy output by an engine. The modelling of engine operation that involves kinetic and potential energy due to acceleration and deceleration of crankshaft has been derived to estimate the indicated torque from instantaneous angular velocity of the engine model (Lim et al., 1994; Schmidt et al., 2000).

6. FEATURE EXTRACTION FOR EMD USING KINETIC ENERGY

Equation 5 expresses the basic calculation for kinetic energy of moving object. It was then derived for particular energy of moving parts in an engine, which are piston, connecting rod, crankshaft, and load kinetic energy. Kinetic energy for linear movement of its gravity centre is expressed on the first term, while kinetic energy for rotational movement of the object around gravity centre is expressed on the second term, refer to (5).

$$E_k = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2$$

(5)

The instantaneous indicated that torque is expressed based on the derivation of energy changes. Moreover, in term of features extraction for EMD, two dimensionless energy indices are defined, refer to (6) and (7). Relative change in kinetic energy during compression stroke is evaluated by compression energy index $CI_i$, while relative change in
kinetic energy during power stroke is evaluated by expansion energy index \( EIi \) (Tinu et al., 2007).

\[
EI_i = \frac{\frac{1}{N} \sum_{j=1}^{N} E_{ci}}{\frac{1}{N} \sum_{j=1}^{N} E_{ci}}
\]

\[
EI_t = \frac{\frac{1}{N} \sum_{j=1}^{N} E_{ct}}{\frac{1}{N} \sum_{j=1}^{N} E_{ct}}
\]

These indices are equivalent to 1 when no misfire or normal combustion is detected in all cylinders. Engine misfire causes the energy to be liberated in the cylinder drop. Thus, corresponding combustion energy index decreases and compression energy index of the next sequence of cylinder in firing order is increases. It is because; more kinetic energy is needed by moving components to compress the gases in the next firing cylinder when less energy is liberated by the combustion of the current misfired cylinder.

Fig. 7 shows the simulated signal of CPS with an indication of the influence of misfire. The simulated result proved that misfire occurred due to torque reduction and it was further affected by the energy liberated by the combustion process since the simulated signal was similar to the actual signal pattern in real engine. Furthermore, the comparison in terms of accuracy percentage could be done between real and modelled signal.

7. USAGE OF EXHAUST GAS TEMPERATURES

Instead of CPS as the probe for misfire detection, some studies found exhaust gas temperature sensor could be used for EMD as well using cycle-by-cycle measurement by the sensor (Gardiner et al., 2007). This method is an alternative for EMD generated by ignition system malfunctions, while the output signal is analysed and classified as either misfire or normal temperature fluctuation. Evaluations on temperature increase and drop section have been done to extract the waveform features due to misfire. When single misfire occurs, the temperature drop remains for around 8 to 10 seconds due to long time constant of the sensor characteristic. Thus, output signal of temperature sensor can be modelled by first order system, refer to (8), to determine temperature reading during and after misfire in order to extract the features of misfire waveform (Tamura et al., 2011).

\[
\begin{align*}
\frac{dT}{dt} &= \frac{1}{\tau} (T_{\text{misfire}} - T) \text{ During misfiring} \\
\frac{dT}{dt} &= \frac{1}{\tau} (T_{\text{normal}} - T) \text{ During normal combustion}
\end{align*}
\]

\( T_{\text{misfire}} \) represents the temperature of exhaust gas when misfire occurs, and \( T_{\text{normal}} \) is the temperature in normal combustion. Time constant, \( \tau \) (tau), of the sensor has unit step response of 0.632 since it is the first order system. Therefore, time constant represents the time taken for the step response to rise and reach 63.2% of its asymptotic value. Temperature waveform features, due to misfire with time constant at around 8 seconds, are shown in Fig. 8, where a single artificial misfire is generated and acquired by the temperature sensor at 0.5 Hz sampling rate. Besides, the threshold of time constant is set to determine the condition of misfire in order to decrease false alarm rate.
Fig. 8. Misfire signal by temperature sensor

Spark plug also has some contributions to the combustion signal analysis since combustion of flame front creates ionization current on the spark plug (Merkisz et al., 2001).

8. OVERALL SYSTEM BLOCK

Misfire could be detected by analysing the ionization signal produced by the centre electrode of spark plug. The system is comprised of two elements, which are 20 MΩ isolation resistor and a connector that is attach on the spark plug distributor cap to acquire combustion signal for the input to the electronic circuit, besides activating a warning light when excessive misfire occurs (Johnson and Rado, 1978).

Fig. 9 shows the block diagram of signal acquisition and the analysed circuit for on board EMD system. In addition, exhaust gas contains HC, NOx, CO, CO2, O2, and water vapour that changes in different combustion conditions. Thus, the amount of the compositions is measured by using a gas analyser machine, which could also analyse misfire diagnosis. It can be done based on matter-element model and extended correlation function, which are directly recognized by relation indices (Ye, 2009). Matter-element model is set with three different conditions of engine; no misfire, slight misfire, and severe misfire. The model is trained based on three different conditions by field test. Table 1 shows the exhaust emission testing data in accordance to verify misfire. EMD was accomplished when the relation index achieved their maximum or 1, as highlighted in Table 2.

<table>
<thead>
<tr>
<th>Actual Fault Types</th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
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<tr>
<td>455 (10^4)</td>
<td>4.7</td>
<td>33</td>
<td>4.8</td>
</tr>
<tr>
<td>572 (10^4)</td>
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<td>4.2</td>
</tr>
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<td>86</td>
<td>4.53</td>
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</tr>
<tr>
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</tr>
<tr>
<td>4220 (10^4)</td>
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<td>188</td>
<td>1.94</td>
</tr>
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<td>189 (10^3)</td>
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<td>91</td>
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</tr>
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</tr>
<tr>
<td>551 (10^4)</td>
<td>8.5</td>
<td>50</td>
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Table 2 Relation indices and diagnosis results

<table>
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<tr>
<th>Relation Indices ( \beta_1 )</th>
<th>Diagnosis Results</th>
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<tr>
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<tr>
<td>(0.1570)</td>
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9. DISCUSSION AND CONCLUSION

Based on various methods to achieve EMD robustness system, in line with emission regulation standard, improvement is still needed for each signal pre-processing or algorithm and the method has its own limitation for various misfire conditions. The use of CPS is popular as many studies and its development have considered the usage of CPS for EMD purpose. However, CPS produces a lot of noise and a high false alarm rate because there are many conditions that could be related to engine speed reduction or fluctuation, such as rough road disturbances, gear changing especially in manual transmission, cylinder-to-cylinder variation, and tooth machining errors where the tooth width are not same (Naik, 2004). Thus, instead of complex algorithm for EMD, improvement has to be made in terms of manufacturing to reduce the disturbances, which gives the method lack of robustness compared to the rest.
Furthermore, in terms of intermittent and continuous misfire, development of algorithm using CPS has been done separately since different algorithms are needed to filter different types of noise for each condition. It would be complex if microcontroller is implemented for online EMD. Although there are simpler algorithms by using temperature sensor, they could not detect how many continuous misfire occurred due to long time constant of sensor. Thus, it could not adapt emission standard requirement, which needs to count the occurrences of misfire. Besides, ionization signal acquisition on spark plug restricts intermittent misfire detection because the system is only stable for excessive misfire, which occurs continuously.

Other than that, the usage of gas analyser had been found to be more efficient compared to the other methods due to its simple algorithm and robust EMD. However, the gas analyser machine is too expensive as it could exceed hundred thousand dollars for each vehicle. The method of gas analysing could be the most efficient system for EMD as the relation of combustion with the gas analyser sensor is more logical compared to CPS, which are widely used at present. Thus, some approaches of using wideband oxygen sensor had been conducted for misfire analysis to make the system cheaper. Moreover, instantaneous oxygen content in exhaust gas contributes to the spike of oxygen sensor signal when misfire occurs and EMD system using wideband oxygen sensor is reliable up to 5000 RPM engine speed of single cylinder motorcycle engine (Amadou et al., 2013, Wang et al., 2020). Although the oxygen sensor can only detect the amount of oxygen in gas emission, instead of all matter elements using gas analyser, it is still possible to be an efficient system since the amount of oxygen in exhaust emission is more influenced by misfire.

REFERENCES


