Development of CPS signal acquisition algorithms for knocking identification and engine diagnosis system in industrial CRDI engine

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Abstract
If knocking occurs, it will result in loss of engine power as well as severe damage to engine. Therefore, it is very significant to monitor knocking. Generally, a practical method of monitoring knocking is to use a knocking sensor. However, by this method it is not possible to distinguish between engine’s own vibrations and knocking if the vibrations match up with the range of the knocking sensor signal for the use of detection of knocking. In this study, knocking was diagnosed by way of using the signals of CKP sensor which is basically installed in the engine, instead of using such a problematic knocking sensor. Moreover, a mobile diagnostic system based on OBD-II for industrial CRDI engine has been developed. Since the developed engine diagnosis system makes it possible for an administrator to monitor automotive information in real time without any other equipment, the person may promptly respond to occurrence of malfunction in engine.

Keywords: CPS(Crankshaft Position Sensor : CKP), CMP(Camshaft Position Sensor : TDC), Long tooth, OBD-II, Knocking

1. Introduction
1.1. Background and Purpose of This Study

An internal-combustion engine generates power with force pushing down on the top of the piston by the ignition and explosion of the fuel/air mixture at a precise timing. At this time, if the mixture is unusually ignited and exploded at the other times rather than the “precise timing”, improper combustion occurs followed by exceptionally high pressure as a result of which the piston hits the cylinder. Such a phenomenon is called knocking[1-3].

Strong shockwaves caused by knocking destroy the thermal boundary layer between the combustion chamber and the surface of cylinder, resulting in sharp increase in the amount of heat transferred to the surface of cylinder. On this account, surface ignition occurs on the cylinder head and piston, and the function and efficiency of engine deteriorate. In addition, a sharp increase in pressure which partially occurs in the combustion chamber causes vibrations of cylinder block. If such a condition continues, shockwaves function as fatigue load over all the engine parts, which damages the components of engine [4-6]. Therefore, it is very significant to detect knocking.

It is a general and practical method of using a knocking sensor detecting vibration signals in order to diagnose knocking. When knocking is identified with the sensor adhered to the cylinder, however, there is a difficulty in making an accurate diagnosis because it is impossible to distinguish between vibrations caused by knocking and automobile’s own vibrations. In order to solve this problem, it is necessary to install an extra sensor for detection of automobile vibrations besides the sensor adhered to the cylinder. Then, this would affect the automobile weight and bring on assembling matters such as the location to install the sensors during the course of assembly. The number of knocking sensors is a factor that affects the weight of automobile, and the weight influences the fuel efficiency. Of course, a question may arise in regard to how much the weight of the two sensors would affect the weight of automobile but in case of automobiles recently manufactured, various sensors and convenient equipments are installed, and the efforts to reduce the weight of automobile have been made. Moreover, since knocking detection may differ depending on the location of the knocking sensor, if knocking...
can be detected by another method besides the knocking sensor, such a study is needed. By this reason, this study intends to make a detection of knocking by using a built-in sensor of vehicle instead of the knocking sensor which is separately attached thereto. Such a built-in sensor is called crankshaft position (“CKP”) sensor. As the most significant sensor to determine the amount and timing of basic fuel injection with calculation of engine rpm and crank angle, the CKP sensor detects the location of tone wheel [7-9]. Knocking can be detected by using such features of this sensor and knocking detection can be more accurate together with use of a camshaft position (“CMP”) sensor to verify knocking in each cylinder.

2. Development and Implementation of Signal Collection Algorithms

As shown in Figure 1, ECU controls knocking by way of receiving knocking signals from the knocking sensor. In this study, among input values of CRDI system, the values of the CKP and CMP sensors for use of determining the injection timing at the time of engine start, instead of the knocking sensor, were used to detect knocking. The CKP sensor described in Fig.1 is the sensor to be used in this study.

2.1. Waveform analysis of CKP and CMP

In the 4-cycle engine, in order to calculate the ignition timing and fuel injection timing, each stroke's identification and specially knowing exactly when the compression TDC is coming on are important. If what degrees of BTDC (Before Top Dead Center) should be more efficient to ignite can be calculated in advance, the ignition at BTDC can be implemented. The ECU should know reference points (missing tooths) to calculate the exact TDCs (top-dead center) and BDCs (bottom-dead center). After occurring the CMP signal, number 1 TDC is the 19th tooths’ position; based on the missing tooth, this point is before 114°, so that the ignition timing can be known by calculating degrees of the BTDC if the number of tooths from the missing tooth is calculated [7].

In case of 1-3-4-2's ignition order of the 4-stroke cycle engine, the positions of number 1 piston and number 4 piston are always the same. Number 4 is TDC whenever number 1 is TDC, and number 4 is exhaust TDC when number 1 is compression TDC. Therefore, in order to perform the ignition and fuel injection, when the piston is at the TDC, that the TDC is whether a compression TDC or an exhaust TDC should be identified; the existence of the TDC position is calculated by the sensor signal of the crankshaft through the CMP sensor. The calculation principle of the TDC position is as follows: the CMP signal is changed; and then number 1 TDC is the 19th tooth's position from that point measured the long-tooth signal; number 3 TDC is the 30th tooth's position from number 1 TDC; number 4 TDC is the 30th tooth's position from number 3 TDC; and number 2 TDC is the next 30th tooth's position from number 4 TDC [7-9].

2.2. System Configuration

In this study, algorithms, which can provide baselines to identify the car's knocking by collecting control sensor values from the simulator, are implemented. Figure 2 is a
configuration diagram to receive control sensor values from the simulator. On the car or simulator mounted the CRDI engine, through the Encoder or CPS(Crankshaft Position/angle Sensor), to measure the knocking sensor and important engine control sensor, the sensor values are collected by using the DAQ board; the values are transmitted to a laptop via USB communications connected with it; and the values are analysed on it. By using these values, to customize the mapping for the improved. CRDI engine control, an algorithm for knocking identification and correction, which can provide the optimal Knocking identification baseline by analysing and processing the useful sensor information, is implemented.

As shown in Figure 2, data are collected by using NI USB-6529 and BNC-2110 Controller devices; the algorithm is developed based on NI Labview 2010 software with the collected data. Engine simulator device generating CPS and CMP signals of the car mounting a motor to the crankshaft and camshaft devices. To analyse the knocking's identification baseline, several tone wheels were made by putting different angles to the special projection portions and different positions to reference points on the tone wheel of the crankshaft.

![Figure 2. System Configuration](image)

### 2.3. Algorithm Development

The knocking of the vehicle can occur diesel knock when the ignition delay period is getting longer; to prevent this diesel knock, one of the methods is to control the injection timing. Therefore, if algorithms controlling the fuel injection timing and injection amount are implemented, the fuel injection timing can be controlled through the knocking identification.

#### 2.3.1 Knocking identification algorithm

If the measured acceleration is greater than the previous acceleration compared with the acceleration of each CPS as shown in Equation (1), the fuel injection timing is controlled by identifying the knocking[11][12]. Figure 3 is a flowchart of the algorithm determining the knocking.

\[ \Delta t = \text{last timing} - \text{initial timing} = t_1 - t_0 \]  

#### 2.3.2 Long-Tooth identification algorithm

When the signal of the crank angle sensor is input, it is identified as the behavior of the engine; in order to match the timing of the fuel or ignition up to the exact timing and position, the input signal of number 1 cylinder TDC sensor(No.1 TDL = CMP) is used as the base. At this time, in order to determine the fuel injection and ignition timing, an algorithm should be needed to determine exactly whether the input value is Long-tooth or not. When the value of the measured current time is 1.75~4.25 times of that of the previous time, the value is determined as the Long-tooth, and it is used as the signal determining the fuel injection timing.

#### 2.3.3 Engine Balance Correction algorithm
Diagnosing the cause of the engine structure is very important: the number of the cylinder's engine rotation can be detected by using the crank position sensor signal; the calculated data can be used to identify the injector's injection amount variation and the engine body (compression pressure, intake and exhaust valve devices, etc.), so that the total result of every each part can be identified. Almost every engine developed recently gets a crankshaft position sensor, so that the identification of the disparity cylinder is possible by using the speed difference when cranking with a scan tool. The ignition timing is $0^\circ \sim 30^\circ$ after the TDC; For each TDC, number 1 is $0^\circ \sim 30^\circ$, number 3 is $180^\circ \sim 210^\circ$, number 4 is $360^\circ \sim 390^\circ$, and number 2 is $540^\circ \sim 570^\circ$; therefore, whether the cylinder is defective or not can be identified by calculating the average speed of these 4 numbers. Figure 4 is a flowchart of the engine balance correction algorithm.

In order to measure the exact average speed, the cycle, the TDC's start and end angles are directly input to reduce the limit of error of the average speed, as a result of it, whether the cylinder is defective or not can be judged more exactly.

### 3. Development and Implementation of Engine Diagnosis System

By way of using the OBD-II standard, automobile-centered diagnostic equipment was developed to provide driver-centered diagnostic services. By way of using cable and Bluetooth module which is a wireless system, it made it possible to provide real-time communication over signals from automotive malfunction diagnosis and sensor output.

#### 3.1 Design of Bluetooth OBD-II Protocol

The developed OBD-II protocol has been manufactured based on the existing BOD-II standard. This differs from the existing BOD-II standard protocol structure. In case of the OBD-II protocol standard, automotive information of only one PID which was requested can be read and responded. However, the developed industrial automotive OBD-II protocol read all the automotive information and transmits such information at once.

#### 3.1.1 Structure of Bluetooth OBD-II Protocol

The OBD-II message may be obtained from the automotive ECU by using automotive diagnostic tools. As seen in Table 1, the message consists of Header, Data and Checksum and saves 12 bytes of data in total and uses HEX codes.

In case of the proposed OBD-II protocol, it is designed to read the whole sensor information of vehicle by a response message at once when automotive information is requested to ECU. ECU provides 31 types of sensor information which actual service centers practically use. The below Table 2 shows the proposed OBD-II protocol response message structure.
### 3.1.2 Structure of Engine Trouble Codes

There is a function to inform drivers that there is malfunction in the electronic control engine by lighting up the malfunction indicator lamp ("MIL") and to set diagnostic trouble code ("DTC") according to the details of malfunction and to automatically record such codes in the RAM of ECU if there is malfunction in electronic control engine or in exhaust gas related parts. This function was originally to set the BOD in order to easily verify the location to be inspected if automotive malfunction occurs but thanks to speedy development of computers, it came to play a role of conducting ready-test (monitoring of exhaust gas equipment) as well as making freeze frame (function to record DTC on ECU) when malfunction occurs in input and output of ECU (computer). Therefore, a self-diagnosis function is the priority to be inspected when malfunction occurs in the car equipped with electronic control engine.

The below Table 3 shows the structure of DTC response message of ECU.

### Table 3. ECU DTC Response Message Structure

<table>
<thead>
<tr>
<th>Command STX</th>
<th>Command ID</th>
<th>MODE</th>
<th>DTC Code</th>
<th>Checksum</th>
<th>Command ETX</th>
</tr>
</thead>
</table>

### 3.2 Automatic Information Collection Algorithm

In order to collect the information of ECU, data are transmitted through the process as described in the below Figure 5. First of all, if Bluetooth communication is connected, a data request message is transmitted to ECU. If the input request message is identical to 023134303030303030454303, ECU transmits OBD-II response message of 130 bytes to temporary buffers. All the data between STX and ETX are converted into HEX codes and sent. The calculation of Checksum is of longitudinal redundancy check ("LRC") and the lower byte of the sum of data between STX and ETX and Checksum should be zero. If the response message is ACK(0x06) and the Checksum value is 0x00, 31 automotive data of 130 bytes are finally saved.
In order to collect DTC of ECU, such codes are transmitted through the process as described in the below Figure 6. Collection process of ECU diagnostic trouble codes is similar to the automotive information collection algorithm as explained above. First of all, if Bluetooth communication is connected, data request message is sent to ECU. If the input request message is identical to 023135303030303030454203, ECU transmits OBD-II response message of 14 bytes to temporary buffers. Then, if response message is ACK(0x06) and the Checksum is 0x00, automotive information of 14 bytes becomes finally saved.

4. Experiments and Results

4.1 Knocking Identification

In this section, by using values of the sensors collected on the designed simulator, algorithms of knocking identification and engine balance correction are developed. Figure 7 is a screen of the program developed to collect data signals, and it shows waveforms of CPS and TDC signals collected at real-time on the simulator.

![Figure 7. Screen of data signal collection program](image)

Figure 7. Screen of data signal collection program

Figure 8 shows the result of using the knocking identification algorithm calculating the acceleration difference between the current time and the previous time. The long waveform is a reference point(missing tooth); the short one, which is between one missing tooth and another missing tooth, is the position occurring knocking.

![Figure 8. Result Screen of Knocking Identification algorithm](image)

Figure 8. Result Screen of Knocking Identification algorithm

If the value of the current time is 1.75~4.25 times of that of the previous time, this value is identified as a Long-tooth; the 19th projection is then determined as number 1 compression TDC; from this base point, the next 30th projection becomes number 2 TDC; the next 30th projection is number 4 TDC, and finally the next 30th projection becomes number 2 TDC. Figure 9 shows the result of the Long-tooth identification control algorithm.

![Figure 9. Result Screen of the Long-tooth identification algorithm](image)

Figure 9. Result Screen of the Long-tooth identification algorithm
Figure 10 is the result of the engine balance correction algorithm performed. It shows a graph of the average speed up to 6°~36° for each TDC; in order to calculate the average speed exactly, the cycle, the start and end angles of the TDC were input; and then, the average speed was measured, as a result of it, whether the cylinder is defective or not was determined. When checking the result, abnormalities were found from number 3 and number 4 of the cylinder.

4.2 Bluetooth Mobile Application Software for OBD-II Protocol Diagnosis

The following shows a screen used for communication between devices. If clicking the button named “Data Request” in order for application to request the connected device for automotive status information, the connected device transmits the status information to the application. Figure 11 shows status information communication between devices. If phone orders ECU to read status information through communication protocol, ECU sends out a data response. Figure 12 is a screen showing DTC information transmission between devices.

The communication between devices is made with HEX codes, so it is difficult for a user to verify the information instinctively. In order to make a user promptly understand the status information, such information was made go through parsing process so that it may be shown on the screen as in Figure 13. When malfunction occurs in ECU, the concerned trouble codes are searched and if the data which are identical to codes saved in DB exist, information related to such codes are notified. If DTC is found, such found DTC is shown on the screen as in Figure 14.
5. Conclusion

In this study, instead of using a knocking sensor, algorithm to identify knocking by using the CKP sensor which is basically installed in almost all the engines has been developed.

While it is said that a use of knocking sensor is convenient and highly accurate, it cannot be said that it is the best solution for knocking identification because there exists a problem: if internal/external automotive environment and engine condition are not favorable, ignition timing may be delayed due to excessive knocking detection, resulting in power reduction. If there is a method free from such problem, such method should be researched. Therefore, in this study knocking was identified through the difference between angular speeds of the crank by using CKP sensor signals. Factors that cause excessive knocking detection were not applied to this method, so more stable identification of knocking could be made. In addition, through Longtooth identification algorithm, accurate knocking identification was made possible. Since the engine balance also has direct impacts on engine power and durability, algorithm to verify cylinders whose balance is to be adjusted has been developed so that all the cylinders could keep the same balance.

Moreover, with OBD-II protocol, a mobile engine diagnostic system using Bluetooth communication was developed. In this study, instead of handling information that can be controlled only by manufacturing companies, it was made possible to select necessary information only and take control at first hand.

It is unnecessary to passively receive and deal with all the data including even needless one, so the administrator may handle information satisfying his needs only. Therefore, with this system it was made possible that information of engine condition may be identified in real time and that if engine has malfunction, by notifying diagnostic trouble codes and information, the user and administrator may promptly respond to such malfunction.

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