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Paljoo Yoon, Seungbum Park and Myoungho Sunwoo
Hanyang Univ.

Inyong Ohm and K. J. Yoon
Hyundai Motor Co.

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ABSTRACT

The introduction of inexpensive cylinder pressure sensors provides new opportunities for precise engine control. This paper presents a control strategy of spark advance and air-fuel ratio based upon cylinder pressure for spark ignition engines. In order to extend the cylinder pressure based engine control to a wide range of engine speeds, the appropriate choice of control parameters is important as well as essential.

For this control scheme, peak pressure and its location for each cylinder during every engine cycle are the major parameters for controlling the air-fuel ratio and spark timing. However, the conventional method requires the measurement of cylinder pressure at every crank angle degree to determine the peak pressure and its location. In this study, the peak pressure and its location were estimated, using a multi-layer feedforward neural network, which needs only five cylinder pressure samples at -40° , -20° , 0° , 20° , and 40° after TDC.

The neural network plays an important role in mitigating the A/D conversion load of an electronic controller by increasing the sampling interval from 1° crank angle (CA) to 20° CA. The estimated location of the peak pressure can be regarded as a good index for combustion phasing, and can also be used as an MBT control parameter. The peak pressure reflects the air-fuel ratio from rich mixture to lean mixture near the lean misfire limit, and can be used as an air-fuel ratio control parameter as well.

The feasibility of this methodology was closely examined through steady and transient engine operations to control spark advance and air-fuel ratio. Moreover, a commercial two-liter four-cylinder engine was employed in this experiment. The experimental results revealed a favorable agreement between the real MBT and target air-fuel ratio.

INTRODUCTION

Engine research is an important task for emission reduction and fuel economy improvement in vehicles. A lean burn and gasoline direct injection engine was introduced as a new design concept for engines. In accordance with the engine design, specific research in engine control is important in engine performance improvement. As a result of that, improvement in the engine controller performance has been investigated in two ways. One way is a development of a high speed microprocessor and application of advanced nonlinear control algorithms. The other way is an introduction of another sensor measuring the status of the engine combustion such as cylinder pressure, ion-current, or crank-shaft speed variation. [1][2][3][4] In this paper, an engine control algorithm based on combustion pressure is introduced, and the algorithm was examined through experiments in a commercial engine.

Flame development in SI engines is affected by many time-varying operating conditions such as engine speed, load, air-fuel ratio (A/F), coolant temperature, turbulence intensity, and so on. The cylinder pressure reflects flame development in the combustion chamber noticeably, and has been used for analyses and monitoring of the combustion. An introduction of combustion pressure sensors in engine control has merits in on-board diagnostics such as misfire detection and knock detection.

The location of peak pressure (LPP) at MBT is nearly constant for different engine hardware specifications and in a wide range of engine operating conditions. [5] The peak pressure (PP) reflects the mixture strength of the combustion, and can be used as a control parameter of A/F control.

EXPERIMENTAL SETUP

Figure 1 shows the experimental setup for cylinder pressure acquisition and engine control. The engine control system is used either as a set-point controller for combustion pressure analysis or as a closed-loop engine controller by using internal A/D converters. The combustion analysis system measures a cylinder pressure from a Kistler pressure sensor at one sample per one crank angle degree. The engine control system and the combustion analysis system are synchronized by using the identical encoder signals. The A/F is measured by a Bosch LSU4 wide-band lambda sensor.

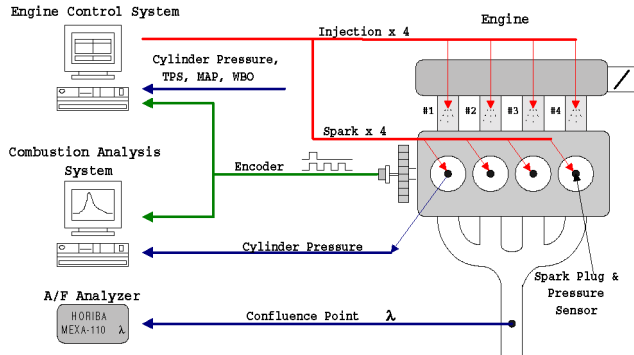


Figure 1. Experimental Setup for a Pressure-based Engine Control System

STEADY-STATE PRESSURE CHARACTERISTICS

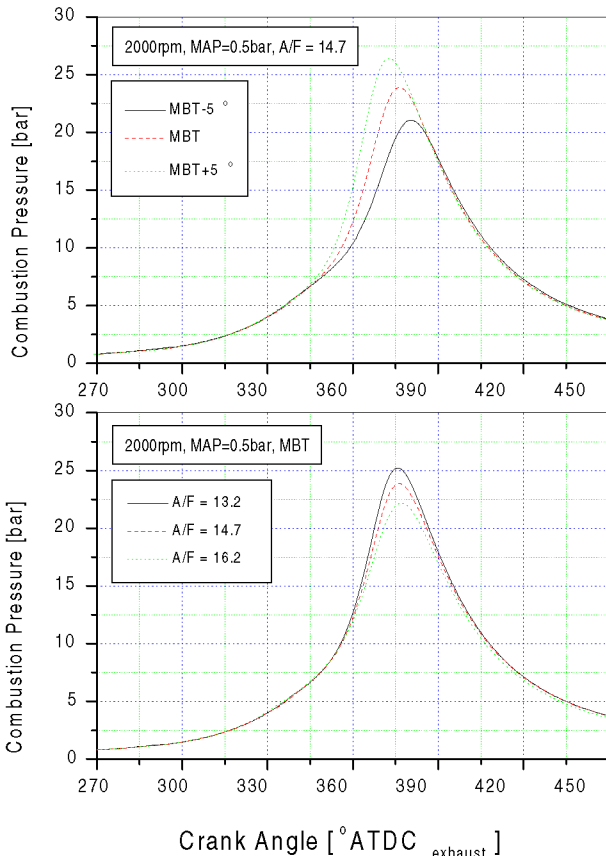


Figure 2. Combustion Characteristics for Various

Combustion Phasing and Air Fuel Ratio

Figure 2 shows the combustion pressure characteristics for different spark advances and A/Fs. Each pressure trace represents the average of 200 cycle combustion pressure. The upper graph represents the effects of spark advance, and the lower graph shows the effects of A/F on cylinder pressure. At constant A/F, the LPP reflects the combustion phasing of each cycle, and at MBT, the PP reflects the A/F of the mixture. In this study, these characteristics of combustion pressure were utilized in controlling MBT and A/F.

CORRELATION OF MBT AND LOCATION OF PEAK PRESSURE

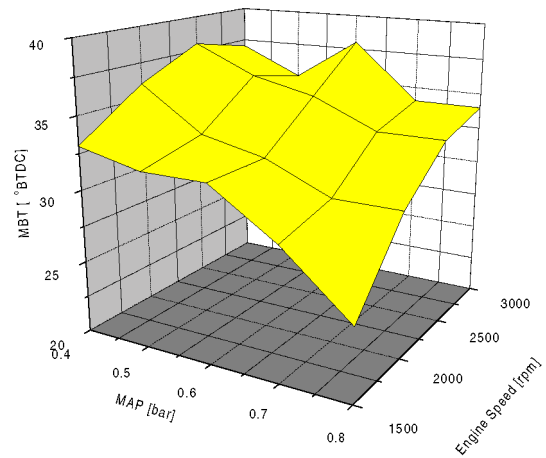


Figure 3. MBT for Various Operating Conditions

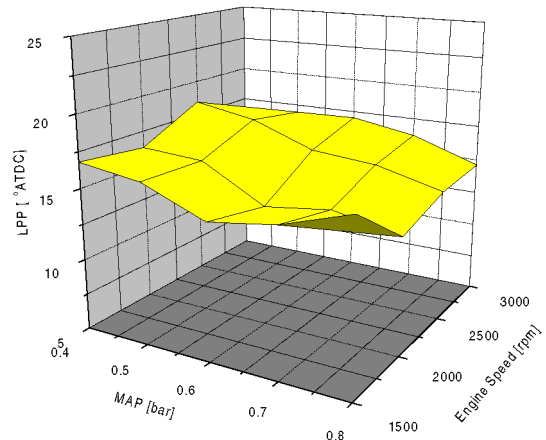


Figure 4. Location of Peak Pressure at MBT for Various Operating Conditions

Figure 3 shows the MBT for various engine speeds (from 1500rpm to 3000rpm), and MAP (from 0.4bar to 0.8bar). The MBT shows a difference of 13° from BTDC 38° to BTDC 25° in this operating region. Figure 4 shows the LPP at MBT for the same operating conditions. The LPP at MBT shows little difference in spite of the variation of engine speed and MAP. The mean value of the LPP at MBT was ATDC 16°, and the target LPP of the spark advance controller was fixed at ATDC 16°.

CORRELATION OF A/F AND PEAK PRESSURE

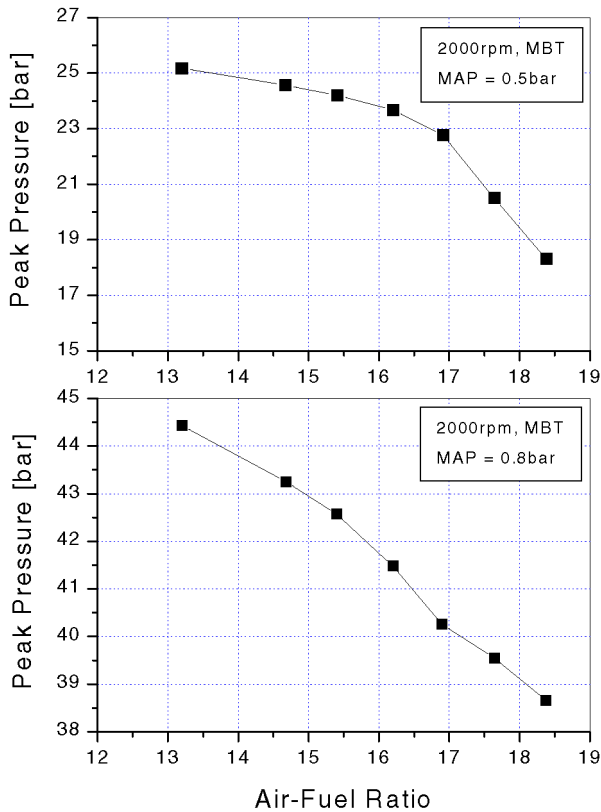


Figure 5. Peak Pressure for Various Air-fuel ratios at Constant Operating Conditions

The PP at the same engine speed and MAP was affected by the spark advance and A/F. Figure 5 shows the PP for various A/Fs when LPP was set to ATDC 16°. The PP shows a strong correlation with A/F, and decreases for leaner mixture. The PP reflects the A/F from rich mixture to lean mixture near the lean misfire limit, and can be used as an A/F control parameter as well.

ESTIMATION OF PEAK PRESSURE AND ITS LOCATION USING A FEEDFORWARD NEURAL NETWORK

The measurement accuracy of PP and LPP is determined by the A/D conversion time of combustion pressure. The sampling interval of one sample per one crank angle degree is adequate for acquiring reasonable values of PP and LPP. However, the application of the A/D converter with such a high sampling rate to an on-board engine controller may cause many problems, especially in the conversion time of analog pressure data to a digital value. In addition, the engine controller should manipulate the data to find the values of PP and LPP. In this study, the PP and LPP were estimated, using a multi-layer feedforward neural network which greatly mitigates the A/D conversion load of the engine controller.

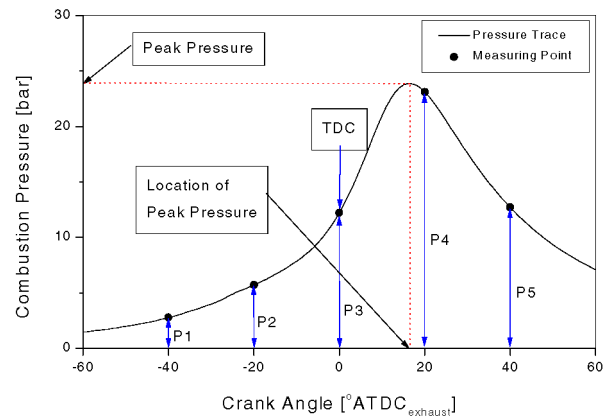


Figure 6. Combustion Pressure Measuring Points for LPP and PP Estimation

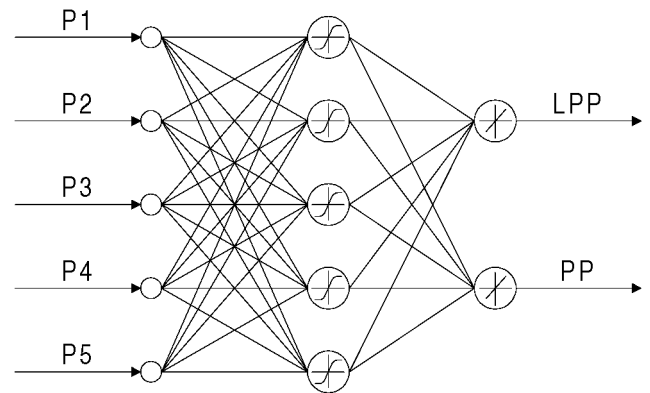


Figure 7. Feedforward Neural Network for PP and LPP estimation

Figure 6 shows the measuring locations of the combustion pressure. The combustion pressure near the firing TDC was measured at five different locations for each engine cycle. The neural network was designed to estimate the PP and LPP using five point cylinder pressures. Figure 7 shows the structure of the multi-layer feedforward neural network for PP and LPP estimation. The neural network consisted of five sigmoid neurons in the hidden layer and two linear neurons in the output layer. Cylinder pressure from various operating conditions was acquired for the training procedure of the neural network. The operating condition is a combination of various engine speeds and MAP. The engine speed varied from 1500rpm to 3000rpm by 500rpm intervals. The MAP varied from 0.4bar to 0.8bar by 0.1bar intervals. In each operating condition, A/F variations at MBT and spark advance variations at the stoichiometric condition were conducted, and there were five data acquisition points for each operating condition. Therefore, the cylinder pressure at 100 points (20 operating conditions \times 5 acquisition points) was acquired for the training of the neural network. Each data set consisted of 200 consecutive cycles of cylinder pressure, and the averaged value of the cylinder pressure was used for

network training. The optimal weights of the neural network were obtained from an error back propagation algorithm using the Levenberg-Marquardt optimization technique for fast convergence. [6] The RMS value of the estimation error of PP was 0.014, as well as that of LPP. These were small enough to be used in real-time control.

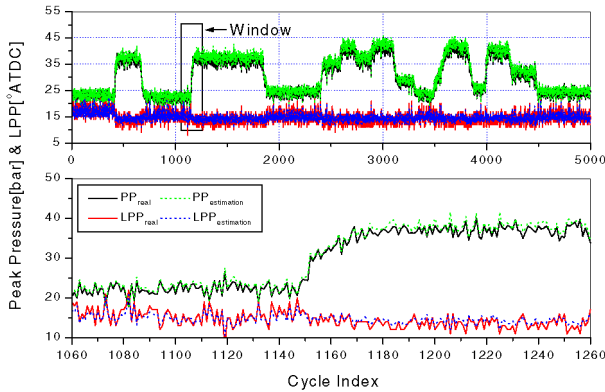


Figure 8. Estimation results of PP and LPP for a transient engine test

Figure 8 shows the experiment results of PP and LPP estimation during a transient engine operation. The lower graph in the figure shows a magnified graph of the rectangular region in the upper figure. The estimated PP and LPP are in favorable agreement with the real PP and LPP.

SPARK ADVANCE CONTROL USING AN ESTIMATED LOCATION OF PEAK PRESSURE

In conventional engine control, the optimal spark advance is determined from the engine speed, load, A/F, and other parameters which affect the flame propagation speed. Many sensors and calibration tables are needed for spark advance control. Furthermore, the MBT finding procedure in gasoline engines is complex and time consuming work in developing engine control system. However, the 50% mass burned crank angle and the LPP are nearly constant for MBT in most operating conditions, and thus it is easy to develop a spark timing controller by using the measured 50% mass burned crank angle or LPP.

In this study, a PID controller for spark advance using an estimated LPP was designed and tested for steady and transient engine operating conditions.

SPARK ADVANCE CONTROL IN A STEADY STATE –
The spark advance controller using an estimated LPP was tested in a steady operating condition: 2000rpm, 0.5bar (MAP), and stoichiometric A/F. Under these conditions, the MBT was BTDC 33°, and the mean value of LPP was ATDC 16.06°. The standard deviation of the LPP was 1.64. Figure 9 shows the control performance of

the spark advance controller which minimizes error between the target LPP (ATDC 16°) and four cycle moving averaged LPP. The feedback of the estimated LPP was started at the cycle index of 2000. The variation of the spark advance was about $\pm 3^\circ$, the mean value of LPP was ATDC 15.83°, and the standard deviation of the LPP was 2.16. The test results shown in Fig. 9 reveal that the standard deviation and the mean offset of the LPP were bigger than those of MBT-based control. Furthermore, a large overshoot of the LPP occurred at the beginning of the control.

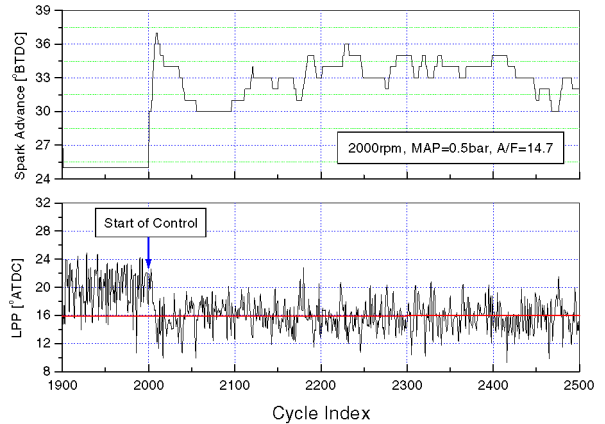


Figure 9. MBT Control using Estimated LPP (four cycle averaging)

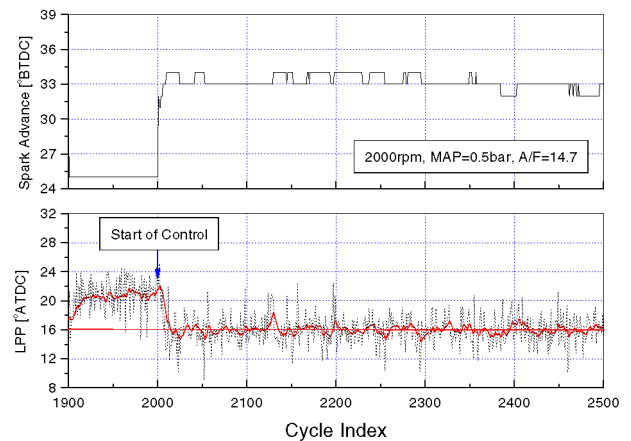


Figure 10. MBT Control using Estimated LPP (First-order filter)

A first-order digital filter was designed to reduce the variation of the LPP in a steady state. Figure 10 shows the results of the spark advance control at the same condition of Figure 9. The solid line represents the filtered LPP and the dotted-line shows the unfiltered estimated LPP. There was no overshoot in the spark advance, and the standard deviation decreased to 1.92. The mean value of the LPP was the same as the target LPP, ATDC 16°. The control performance of the spark advance controller was improved by employing a digital filter.

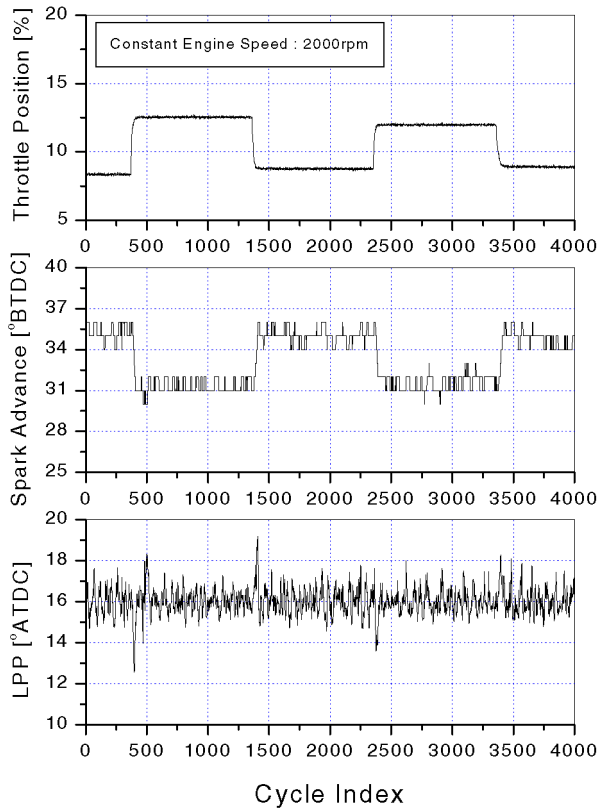


Figure 11. MBT Control using Estimated LPP [Transient Condition]

SPARK ADVANCE CONTROL IN A TRANSIENT STATE – Figure 11 shows the results of the spark advance control in a load transient condition. The engine speed was set to 2000rpm, and the load was changed to a square waveform. The spark advance was controlled to regulate the LPP at ATDC 16°. The controller followed the variations of the load effectively, and there was little variation in spark advance in a steady operating region. The results show that the closed-loop spark advance controller maintains the optimal combustion phasing in spite of the rapid change of the external conditions by monitoring real combustion phenomena.

AIR-FUEL RATIO CONTROL USING ESTIMATED PEAK PRESSURE

The peak pressure was decreased for the leaner mixture at constant manifold pressure and the LPP. The target peak pressure for A/F control was determined by the mean value of the measured peak pressure at constant operating conditions. Figure 12 shows the structure of the A/F controller using peak pressures. The target peak pressure which corresponds to the desired A/F was calculated from the engine speed and MAP. The error of the peak pressure from the target peak pressure was the input of the A/F controller. The base fuel injection quantity was calculated according to engine operating conditions, and was added to the final fuel injection control command as a feedforward path of a control loop. This is a structure similar to the conventional A/F controller using an exhaust gas lambda sensor. However, in the case of

pressure-based control, the role of a lambda sensor was replaced by a cylinder pressure sensor.

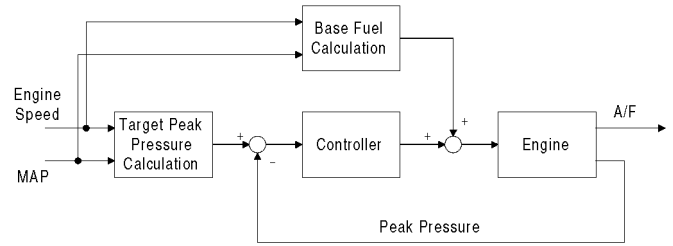


Figure 12. Air-fuel Ratio Controller using Estimated Peak Pressure

Figure 13 shows the results of the A/F control in a steady engine speed and load. The target A/F was changed from 14.7 to 15.4 at the cycle index of 500, and from 15.4 to 14.7 at the cycle index of 1500. The peak pressure was filtered by a second-order digital filter for the stable fuel injection control in spite of the cyclic variations of the PP in the steady state.

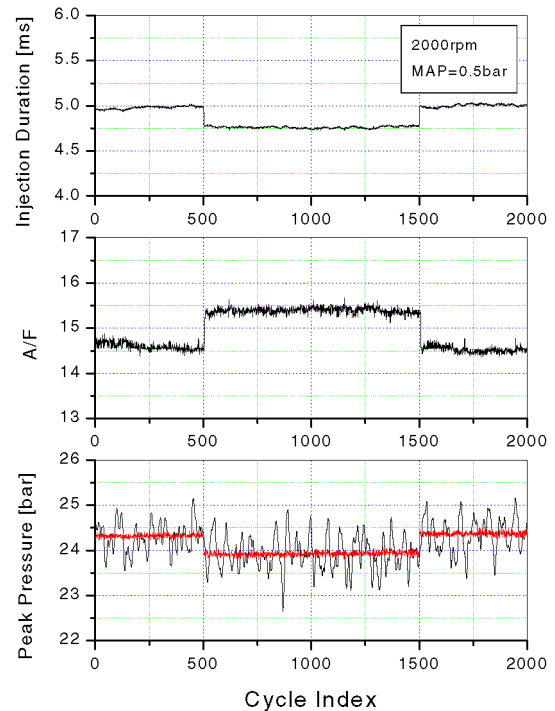


Figure 13. Target A/F Step Change at Constant Operating Conditions

Figure 14 shows the A/F control results at load transient operating conditions. The target A/F was 16.2. The engine speed was set to 2000rpm, and the load was changed to a square waveform. The PP was controlled to follow the target PP. The controller followed the variations of the load effectively, and there was little variation in fuel injection duration in the steady operating region. The results show that the closed-loop A/F controller maintain the desired A/F in spite of the rapid change of the external load. There was little lean or rich spike in the A/F at load transient points. The lean or rich spike can be reduced by use of fuel film compensation techniques.

The RMS value of the error from the target A/F in this test condition was 0.0026.

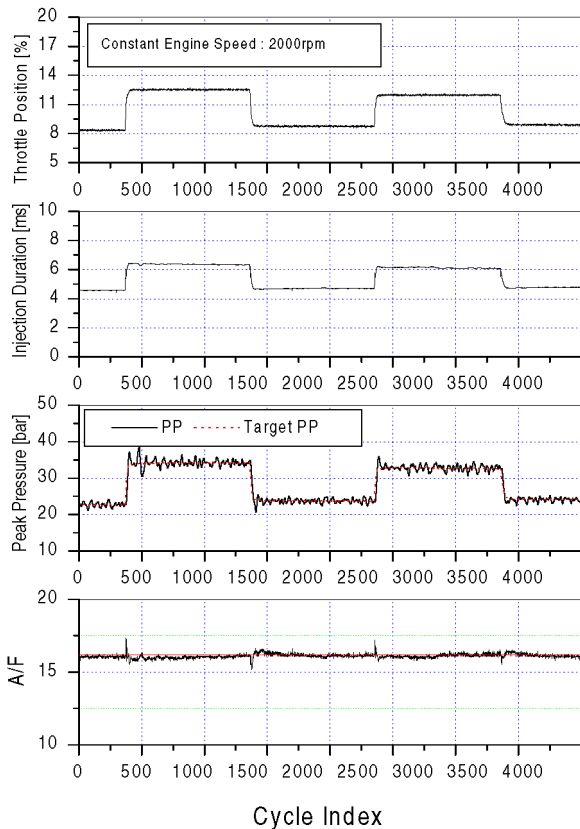


Figure 14. Air-fuel Ratio Control using Estimated Peak Pressure

CONCLUSION

1. The neural network plays an important role in mitigating the A/D conversion load of an electronic engine controller by increasing the sampling interval from 1°CA to 20°CA.
2. The estimated location of the peak pressure can be regarded as a good index for combustion phasing, and can also be used as an MBT control parameter. The location of peak pressure was regulated at ATDC 16° during transient engine operations.
3. The peak pressure reflects the air-fuel ratio from rich mixtures to lean mixtures near the lean misfire limit, and can be used as an air-fuel ratio control parameter as well. The RMS value of the error from the target A/F was 0.0026 during 4000 cycles of the transient load change.
4. The individual cylinder engine control can be realized by the installation of a combustion pressure sensor for each cylinder.

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CONTACT

Myoungho Sunwoo, Associate Professor,
 Dept. of Automotive Engineering, Hanyang University
 17 Haengdang-dong, Sungdong-ku, Seoul 133-791,
 Korea. msunwoo@email.hanyang.ac.kr