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Experimental Study of Combustion Fluctuation Reduction Using In-Cylinder Pressure Estimation in Gasoline Engine

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Abstract. Gasoline engines needs to reduce its negative emission waste and raise its thermal efficiency. Previous studies have shown an improvement of engines by regulating the ignition timing and retaining the engine at certain air-to-fuel ratio. Additional development of the thermal efficiency is anticipated by reducing the oscillation of pressure due to combustion (referred to as combustion fluctuation) during each cycle. Reducing the combustion fluctuations promotes the generation of a stable combustion field and improves fuel consumption. Since the combustion fluctuations are significantly affected by the in-cylinder pressure at compression top dead center (referred to as TDC pressure), the present study proposes a method to estimate the TDC pressure in the next cycle. The estimation was conducted by measuring the in-cylinder pressure at exhaust valve opening in the given cycle. This study also developed the method to reduce the combustion fluctuations by using the TDC pressure estimation and controlling the ignition timing. In our experiments, it was found that the developed methods reduced the fluctuations of the indicated mean effective pressure (IMEP), the maximum in-cylinder pressure, and the TDC pressure by 62.1%, 51.2%, and 38.5%, respectively.

Keywords: Combustion Fluctuation, In-Cylinder Pressure, IMEP, Spark Ignition Engine, Ignition Timing Control.

1. Introduction

In response to the requirements for increasing the fuel efficiency and reducing the harmful exhaust gas generation in gasoline engines, the previous studies have observed some of the regulatory requirements by adjusting the air-to-fuel ratio (A/F), the timing for ignition, and other performance factors of engine [1–9]. However, one factor is not considered as part of improving the variation of pressure in the combustion stroke per cycle. This factor is known as “combustion fluctuation” and degrades the engine performance. Although the techniques such as the lean-burn and the exhaust gas recirculation (EGR) have been proposed for improving the fuel consumption and the exhaust gas emission, they also give an increase in the combustion fluctuation. Some studies have reported that the reduced combustion fluctuation can decrease the harmful exhaust emissions and increase the fuel efficiency [10–16]. Consequently, it is expected to develop a new method that consider the reduction of combustion fluctuation.

The previous studies have revealed several key characteristics of the combustion fluctuation [17–20]. Since the pressure fluctuations in the intake, compression, and expansion strokes are extremely small in comparison with those in the combustion stroke, these small fluctuations can be regarded as identical in successive cycles. Accordingly, the combustion fluctuation is dependent on the residual gas and the indicated mean effective pressure (IMEP) that is defined as the indicated work divided by the stroke volume. The present study focuses on the correlation between the combustion fluctuation and the IMEP. The previous studies [21–26] investigated the effects of the IMEP on the various parameters, and it was found that the maximum in-cylinder pressure has a huge effect on the IMEP. As described later, the in-cylinder pressure at compression top dead center (referred to as TDC pressure) is strongly correlated with the maximum in-cylinder pressure. This means that the pressure during TDC has the potential to be an indicator for combustion fluctuation. For the quantitative evaluation of these relation, the in-cylinder pressure data were acquired by using pressure sensors. The highly robust sensors have been designed before for controlling the engine [27–36]. However, these sensors have not been installed in gasoline engines due to its relatively high expense compared to the small engine control effect. In the present study, it is expected to develop the high-performance control method using the pressure sensors.

The objectives of the present study are to propose the method using the in-cylinder pressure sensor for the estimation of the TDC pressure in the next cycle and to develop two types of methods for maintaining a constant TDC pressure. Maintaining constant TDC pressure is done by using the proposed estimation methods and controlling the ignition timing, which causes keeping the maximum in-cylinder pressure and the IMEP as well as reducing the combustion fluctuation. Furthermore, the present reduction method was validated by applying these methods to a single cylinder at a given engine speed under the lean-burn conditions which are equal to the high A/F conditions.

2. Experimental Setup and Condition

2.1. Experimental Setup

Figure 1 shows the experimental system configuration including the electronic control unit (ECU) for the ignition timing and A/F control, and Table 1 lists the specifications of the engine used in the experiments. The engine speed was maintained under constant value by using the low inertia dynamometer (Horiba, Ltd., Dynas3 LI250), whose absorbing rated power is 250 kW and absorbing rated speed is 4980 r.min^{-1}. The temperatures of cooling water and lubricating oil were held constant at 80°C by using temperature regulator. The cylinder head was equipped with the piezoelectric pressure transducer (Kistler Japan Co., Ltd., 6117A) to measure the in-cylinder pressure with 0.001 MPa resolution at 1 °CA intervals in conjunction with the rotary encoder, along with the data logger. On the other hand, the required resolution for the pressure measurement in the present study was on the order of 1/100 for the TDC pressure (0.01 MPa), which means that the pressure sensor used in the present study satisfied the required resolution. The influence of the drift in the obtained data was negligible, because the pressure data were adjusted for the bottom dead center (BDC) pressure at the intake stroke in each cycle. The A/F sensor (Horiba, Ltd, MEXA-720NOx) was set at 370 mm downstream from the cylinder block. The newly developed method was used to control the ignition timing for the actual engine, which was programmed by using the numerical analysis software (MathWorks, Inc., MATLAB®) and transmitted to the ECU via the multi-channel A/D board (dSPACE GmbH, DS2002).

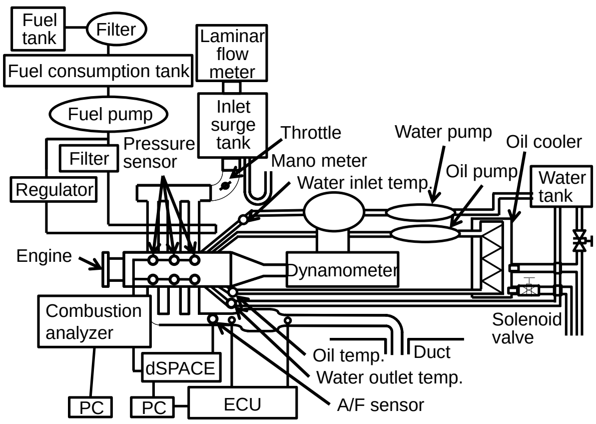

Figure 1. Schematic diagram of the experimental gasoline engine with engine control unit and pressure sensor for pressure measurement in the cylinder

Table 1. Specification of gasoline engine

Type	Gasoline 4 stroke
Layout of engine	V type 6 cylinder
Shape of chamber room	Pent roof type
Displacement	3.456 L
Fuel injection type	EFI, Direct injection

2.2. Experimental Conditions

Table 2 shows the experimental conditions whose condition 1 was used in Section 3 and conditions 2 and 3 were used in Section 4. The experiments under the condition 1 were performed by varying only the A/Fs while the engine speed and the ignition timing were set to be constant. The results were used to propose the estimation method for the TDC pressure in the next cycle by using the in-cylinder pressure in the given cycle and to develop the reduction method of the combustion fluctuation. The experiments described in Section 4 were performed to validate the reduction method developed in Section 3. Both the engine speed and the A/F were kept at the constant value, while the ignition timing was changed either manually (the condition 2, absence of control) or automatically (the condition 3, with control). Without the control conditions, 7 ignition times were manually set and the IMEP from the time evolution of the in-cylinder pressure for each ignition timing condition was evaluated. With the control conditions, the standard ignition timing was set at 35 °CA before TDC, which is the reference ignition timing of original ECU. The IMEP was evaluated when the TDC pressure was in constant value by controlling the ignition timing. For all experimental conditions, the fuel injection rate correction through the feedback control using the oxygen sensor was not conducted.

Table 2. Experimental condition

Condition 1 (for Section 3)

Engine speed	[r.min^{-1}]	1,800
Boost pressure	[kPa]	−66.7
Coolant temperature	[K]	353
Air temperature	[K]	296
Ignition timing (BTDC)	[°CA]	35
Air-to-fuel ratio	[–]	14.7, 16.0, 16.5, 17.0

Condition 2 (for Section 4)

Engine speed	[r.min^{-1}]	1,800
Boost pressure	[kPa]	−66.7
Coolant temperature	[K]	353
Air temperature	[K]	296
Ignition timing (BTDC)	[°CA]	29, 31, 33, 35, 37, 39, 41
Air-to-fuel ratio	[–]	17.0
Ignition timing control		Without control

Condition 3 (for Section 4)

Engine speed	[r.min^{-1}]	1,800
Boost pressure	[kPa]	−66.7
Coolant temperature	[K]	353
Air temperature	[K]	296
Ignition timing (BTDC)	[°CA]	35 (changed by control)
Air-to-fuel ratio	[–]	17.0
Ignition timing control		With control

3. Development of Reduction Method of Combustion Fluctuation

3.1. Relationship between IMEP and TDC Pressure

Figure 2 shows in-cylinder pressure curves in respect to the angle of the crank, which were obtained for a randomly selected set of five cycles. The ignition timing of this condition was set at 35 °CA before TDC (thus θ = 325 °CA). We could observe the combustion fluctuations in the approximate range of 10 °CA before TDC (thus θ = 350 °CA) to 20 °CA after TDC (θ = 380 °CA), which should be reduced by maintaining almost the same in-cylinder pressure curves during each cycle. The IMEP is generally used as an indicator to the state of combustion in gasoline engines and its calculation requires the integration of the in-cylinder pressure during each cycle. Thus, the IMEP is inappropriate to a control indicator for the reduction of combustion fluctuation.

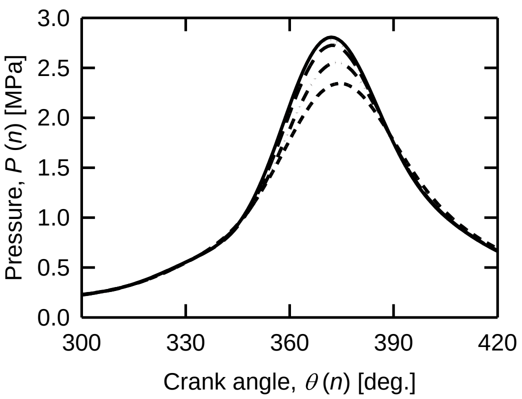

Figure 2. Pressure as function of crank angle under condition 1 at A/F of 17.0

The previous studies show the qualitative correlation between the IMEP, P_{IMEP}, and the maximum in-cylinder pressure, P_{max}. Figure 3 plots the time evolutions of the IMEP and the ultimate in-cylinder pressure with condition 1 at A/F of 17.0. Figure 4 shows the distributions of the probability density functions, in which ΔP_{IMEP} and ΔP_{max} represent the absolute difference values from the 500 cycle average P_{IMEP} and those from the 500 cycle average P_{max}, respectively. The quantitative evaluation, the standard deviation, the averaged value, and the oscillation ratio of P_{IMEP} and P_{max} under the condition 1 at each of the four A/Fs are shown in Table 3, where the fluctuation ratio was defined as the standard deviation divided by the average value. It is obvious from Table 3 that the fluctuation ratios for both P_{IMEP} and P_{max} increase with increasing the A/F (i.e., the lean-burn condition), which suggests that there is a correlation between the above two parameters.

Figure 5 shows the correlation between the IMEP and the ultimate in-cylinder pressure with condition 1 at the A/F of 17.0, and the solid line indicates the correlation line. The figure provides the quantitative confirmation of the positive correlation between the two

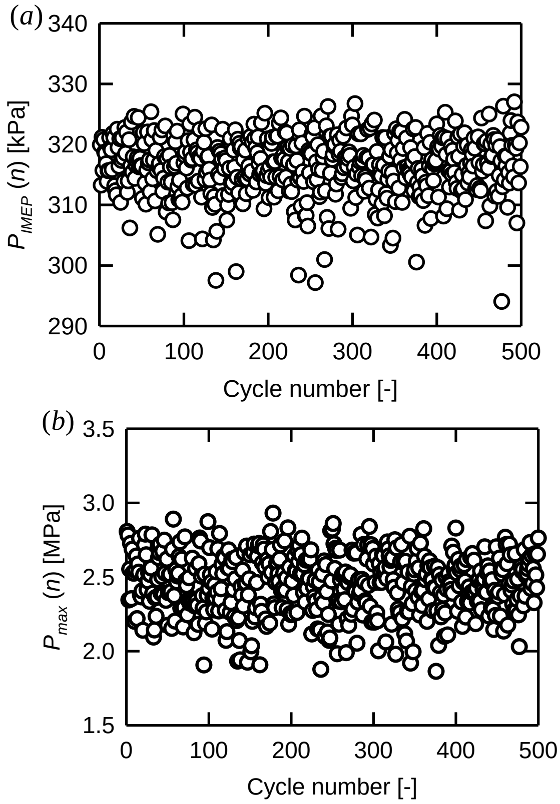

Figure 3. Evolution of time for (*a*) IMEP and (*b*) ultimate in-cylinder pressure with condition 1 at A/F of 17.0

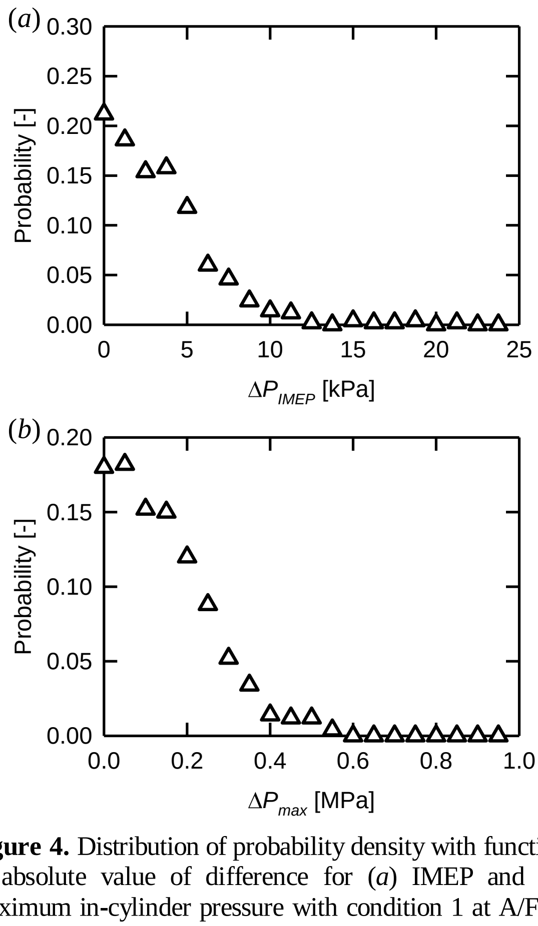

Figure 4. Distribution of probability density with function of absolute value of difference for (*a*) IMEP and (*b*) maximum in-cylinder pressure with condition 1 at A/F of 17.0

parameters with a correlation coefficient of 0.59, and the similar correlation coefficients were obtained for all four A/Fs in the condition 1. Since the correlation coefficient larger than 0.5 was regarded as indicating the moderately strong correlation, the combustion fluctuation was evaluated by using P_{max}, instead of P_{IMEP}. As shown in Table 3, since the largest fluctuation ratio was observed at the A/F of 17.0, we developed the reduction method of the combustion fluctuation (described in Section 3.2) and validated the effectiveness of the method (described in Section 4) under the condition of the A/F of 17.0.

Table 3. Standard deviation average value and fluctuation ratio of (*a*) IMEP and (*b*) ultimate in-cylinder pressure with condition 1 at each A/F

(*a*) IMEP, P_{IMEP}

Air-to-fuel ratio [–]	Average [kPa]	Standard deviation [kPa]	Fluctuation ratio [%]
14.7	355	3.45	0.97
16.0	339	3.66	1.08
16.5	329	3.82	1.16
17.0	316	5.03	1.59

(*b*) Maximum in-cylinder pressure, P_{max}

Air-to-fuel ratio [–]	Average [MPa]	Standard deviation [MPa]	Fluctuation ratio [%]
14.7	2.91	0.17	5.95
16.0	2.75	0.16	5.97
16.5	2.62	0.17	6.42
17.0	2.45	0.20	8.23

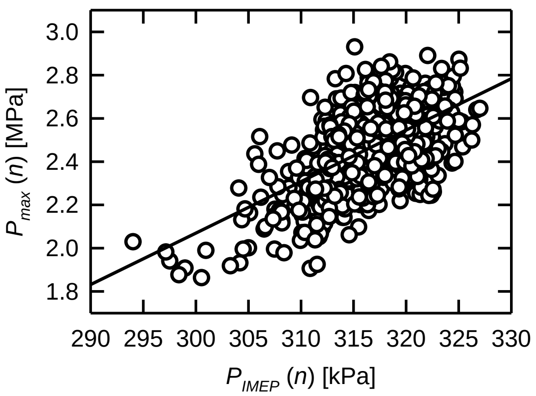

Figure 5. Relationship between maximum in-cylinder pressure and IMEP under condition 1 at A/F of 17.0; solid line indicates the correlation line

Furthermore, in accordance with the computational processing speed and the data transmission speed, the in-cylinder pressure used in the control was obtained at 0.25 ms intervals for the implementation of the procedure developed in Section 3.2. With the engine speed of 1,800 r.min^{-1} used throughout this study, this interval corresponded to the sampling rate for every 2.7 °CA. Since the maximum in-cylinder pressure, P_{max}, occurs at a different crank angle in each cycle, it is necessary to obtain the pressure data at the sampling rate for every 1 °CA at least. Hence, the use of the maximum in-cylinder pressure for controlling the ignition timing process with the present system would result in the decreased accuracy (in the future, an increase in computational processing speed and data transmission speed may overcome this shortcoming). The present study investigated the tentative use of the TDC pressure, P_{TDC}, as the control indicator, in place of P_{max}. Figure 6 shows the correlation between the TDC pressure and the maximum in-cylinder pressure, and the correlation coefficient between the two pressures was estimated to be 0.95. This result indicated that P_{TDC} was substituted for P_{max} as the control indicator for the reduction of combustion fluctuation under the present conditions shown in Table 2.

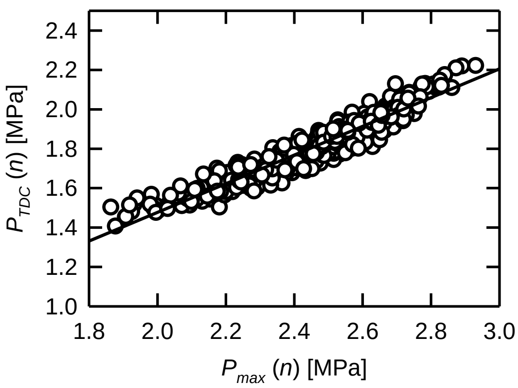

Figure 6. Relationship between TDC pressure and maximum in-cylinder pressure under condition 1 at A/F of 17.0

3.2. Combustion Fluctuation Reduction Method by Using TDC Pressure

As described in Section 3.1, the TDC pressure is the indicator of combustion fluctuation. To accommodate such condition, we considered a method for the estimation of the TDC pressure in the next cycle and proposed a method for the reduction of combustion fluctuation based on the estimated TDC pressure through the ignition timing control. The previous studies [37–40] showed that the above pressures are dependent on the in-cylinder pressure at the exhaust-valve opening (referred to as EVO pressure) and the in-cylinder pressure at the intake-valve opening (referred to as IVO pressure), and the inter-cycle changes in the IVO pressure were much smaller than those in the EVO pressure. Thus, the TDC pressure, P_{TDC}, might be expected to correlate closely to the EVO pressure, P_4. If the cycle-averaged TDC pressure in the next cycle, $P_{TDC\text{-}ave}$ (n+1), could be predicted by measuring the cycle-averaged EVO pressure in the given cycle, $P_{4\text{-}ave}$ (n), a similar TDC pressure in successive cycles by adjusting the ignition timing would be obtained, and thereby reduce the combustion fluctuation. Hence, Figure 7 shows the correlation between $P_{TDC\text{-}ave}$ (n+1) and $P_{4\text{-}ave}$ (n), where correlation coefficient was evaluated to be –0.88. Since this relation had the strong negative correlation, the empirical formula was expressed with the following equation:

$$P_{TDC-ave}\left(n+1\right) = -33.8 P_{4-ave}\left(n\right) + 10.8 . \quad (1)$$

As shown in Figure 7, the above parameters were evaluated using the cycle-averaged values. This was attributed to decrease the stochastic variations of the combustion fluctuation, which causes increase in the estimation accuracy of Eq. (1). Figure 8 shows the correlation coefficient between the experimental data and the estimated values for the TDC pressure, which clearly indicates that the estimation accuracy was substantially increased by averaging over more than 5 cycles. In this section, the following reduction method of the combustion fluctuation was developed by controlling the ignition timing in the next cycle with the averaged data from the preceding 5-cycles (including the given cycle).

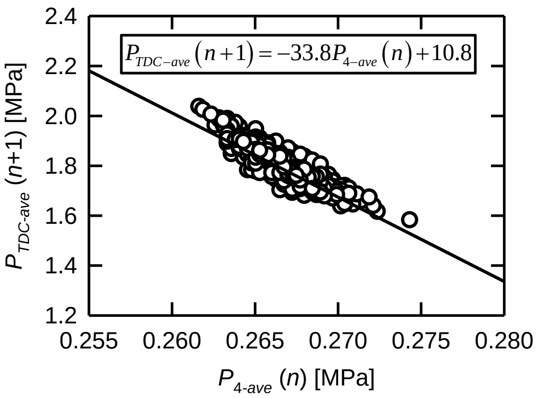

Figure 7. Relationship between cycle-averaged TDC pressure and cycle-averaged EVO pressure under condition 1 at A/F of 17.0

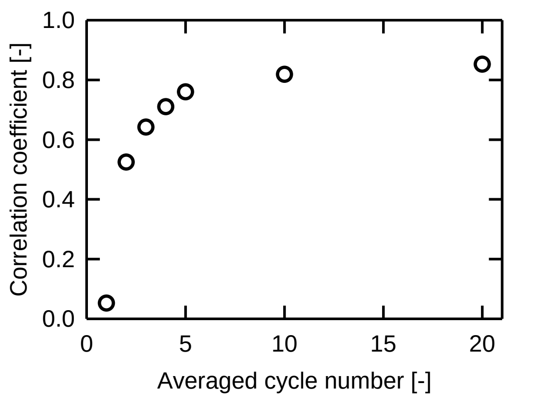

Figure 8. Relationship among correlation coefficient and averaged cycle number

The approach for the prediction of the ignition timing in next cycle to achieve a constant TDC pressure was essentially as follows: The previous studies noted that the variations in the TDC pressure or the maximum in-cylinder pressure were induced by the change in the combustion initiation position during each cycle. Thus, the present study examined the correlation between the TDC pressure, $P_{TDC\text{-}ave}$ (n+1), and the combustion initiation position, θ_{10} (n+1), (defined as the crank angle at 10th part of the maximum rate of heat generation in the present study), as shown in Figure 9. The empirical formula for this correlation was derived with the following equation:

$$\theta_{10}(n+1) = -30.0P_{TDC}(n+1) + 376\,. \tag{2}$$

This equation could then be applied to estimate the combustion initiation position of the TDC pressure calculated from Eq. (1). Figure 10 shows the correlation between θ_{10} (n+1) and the ignition timing, θ_{ig} (n+1) (defined as the spark advance from TDC), and the empirical equation was represented as:

$$\theta_{ig}(n+1) = -1.58\theta_{10}(n+1) + 585\,. \tag{3}$$

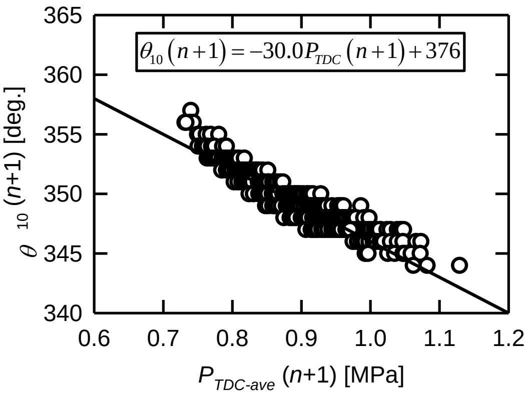

Figure 9. Relationship among the 10th part of crank angle with ultimate rate of heat generation and cycle-averaged TDC pressure with condition 1 at A/F of 17.0

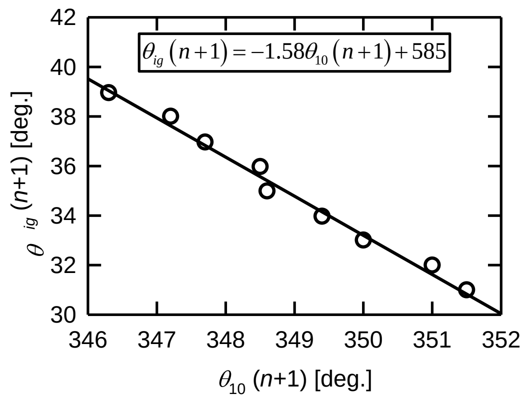

Figure 10. Relationship among ignition timing before TDC and the 10th part of crank angle with ultimate rate of heat generation with condition 1 at A/F of 17.0

This equation indicated that the ignition timing of 1.58 °CA could be advanced or retarded by changing the combustion initiation position of 1 °CA. In order to provide the constant estimated combustion initiation position for the next cycle, the ignition timing correction angle, $\Delta\theta_{SA}$ (n+1), was introduced by the following equation:

$$\Delta\theta_{SA}(n+1) = -1.58\left(\theta_{10}(n+1) - \theta_{set}\right), \tag{4}$$

where θ_{set} [°CA] was the target crank angle of the combustion initiation position. Figure 11 shows the schematic diagram of the ignition timing correction technique for the reduction of the combustion fluctuation, which procedure was essentially as follows:

(1) The 5-cycle-averaged EVO pressure, $P_{4\text{-}ave}$ (n), was measured by using the pressure sensor, and the 5-cycle-averaged TDC pressure in the next cycle, $P_{TDC\text{-}ave}$ (n+1) was estimated by applying $P_{4\text{-}ave}$ (n) to Eq. (1).

(2) Since the variation in the TDC pressure was caused by a change in the combustion initiation position during each cycle, the combustion initiation position in the next cycle, θ_{10} (n+1), was estimated by applying $P_{TDC\text{-}ave}$ (n+1) to Eq. (2).

(3) The ignition timing was corrected by applying Eq. (4) to θ_{10} (n+1), which causes to keep the TDC pressure constant and reduce the combustion fluctuation.

Additionally, the robust performance of the developed ignition timing correction technique was discussed in Section 4. The target values in Sections 4.1 and 4.2 were set at the combustion initiation position represented as the averaged TDC pressure in the preceding 5 cycles (hereinafter referred to as average correction technique) and that as the maximum TDC pressure in the preceding 5 cycles (hereinafter referred to as maximum correction technique).

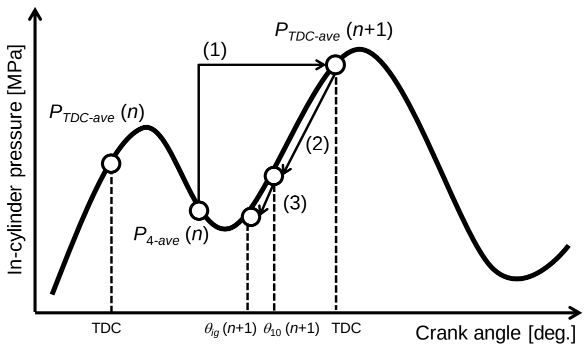

Figure 11. Review of developed method to decrease combustion oscillation by estimating TDC pressure and controlling ignition timing

4. Results and Discussion

4.1. Combustion Fluctuation Reduction by Average Correction Technique

The experiments were performed under the condition 3 by controlling the ignition timing in the next cycle with the average correction technique. Table 4 summarizes the average values, the standard deviations, the fluctuation ratios (well-defined as the standard deviation divided by the average value) and the rate of reduction (defined as the percentage change from the fluctuation ratio of condition 2 to the fluctuation ratio of condition 3) of the IMEP, P_{IMEP}, the maximum in-cylinder pressure, P_{max}, and the TDC pressure, P_{TDC}, under the conditions 2 and 3. Based on the fluctuation ratios in the IMEP and the maximum in-cylinder pressure, their ratios under the condition 3 were smaller than those under the condition 2, and thus, the average correction technique resulted in decreasing the fluctuation of the IMEP and the maximum in-cylinder pressure slightly, compared with the condition without the correction technique, which was identified as reducing the combustion fluctuation. However, Table 4 exhibits that only the fluctuation ratio in the TDC pressure was increased by using the average correction technique, and this was attributed to the ignition timing correction in the retard direction.

Table 4. Average value, standard deviation, fluctuation ratio and rate of reduction of (*a*) IMEP, (*b*) maximum in-cylinder pressure, and (*c*) TDC pressure under conditions 2 and 3 with control by using average correction technique

(*a*) IMEP, P_{IMEP}

	Average [kPa]	**Standard deviation [kPa]**	**Fluctuation ratio [%]**	**Rate of reduction [%]**
Condition 2	316	5.03	1.59	–
Condition 3	320	3.93	1.23	22.7

(*b*) Ultimate in-cylinder pressure, P_{max}

	Average [MPa]	**Standard deviation [MPa]**	**Fluctuation ratio [%]**	**Rate of reduction [%]**
Condition 2	2.45	0.20	8.24	–
Condition 3	2.70	0.19	6.93	15.9

(*c*) TDC pressure, P_{TDC}

	Average [MPa]	**Standard deviation [MPa]**	**Fluctuation ratio [%]**	**Rate of reduction [%]**
Condition 2	1.80	0.15	8.55	–
Condition 3	2.05	0.19	9.15	−7.07

In a typical example, the maximum and minimum ignition timing correction angles, $\Delta\theta_{SA}$, were +3.8 °CA and −5.7 °CA, and it continued to alternate between the advance and retard directions in approximately every 10 cycles. This ignition timing correction in the retard direction was caused by condition as follows: When examining the measured pressure data, approximately 10% of the TDC pressures showed extremely low values due to the stochastic variations of the combustion fluctuation. Since the target value was set at the average of the TDC pressure in the preceding 5 cycles, the use of the extremely low pressure data generated the lower target value. Afterward, the ignition timing was corrected in the retard direction. This fact indicates that the TDC pressure was hardly changed although the maximum in-cylinder pressure was fluctuated, because the combustion initiation position was also retarded and the pressure at approximately 350 °CA in Figure 2 was measured as the TDC pressure. For the above case, since there was the weak correlation between the maximum in-cylinder pressure and the TDC pressure, the reduction method with the average correction technique could not be applied to this case. Therefore, the lack of a limit on the ignition timing correction angle ($\Delta\theta_{SA}$ (n+1)) led to the significant correction of the ignition timing in the retard direction and to an increase in the fluctuation ratio in the TDC pressure. Based on the above facts, we considered that the effect of the extremely low TDC pressure could be decreased by using the maximum TDC pressure in the preceding 5 cycles as the target value, and the results using the maximum correction technique are discussed in Section 4.2.

4.2. Combustion Fluctuation Reduction by Maximum Correction Technique

The experiments were performed under the condition 3 by controlling the ignition timing in the next cycle with the maximum correction technique. Table 5 summarizes the average values, the standard deviations, the fluctuation ratios and the rate of reduction of the IMEP, P_{IMEP}, the maximum in-cylinder pressure, P_{max}, and the TDC pressure, P_{TDC}, under the conditions 2 and 3. Since the target value was set at the maximum TDC pressure in the preceding 5 cycles, it was suggested that the control of the ignition timing gives rise to all the pressures listed in Table 5 and decrease their standard deviations. Under the present experimental conditions, the maximum and the minimum ignition timing correction angles, $\Delta\theta_{SA}$ (n+1), were +3.8 °CA and ±0.0 °CA, respectively, which means that there was no correction of ignition timing in the retard direction. With the maximum correction technique, the fluctuation ratios of all three parameters were evaluated to be 0.60%, 4.02% and 5.26%, respectively, which was greater reduction in the combustion fluctuation than the results without the correction technique (1.59%, 8.24% and 8.55%) and those with the average correction technique (1.23%, 6.93% and 9.15%).

Table 5. Standard deviation, rate of reduction, average value, and fluctuation ratio of (a) IMEP, (b) ultimate in-cylinder pressure, and (c) TDC pressure under conditions 2 and 3 using control by utilizing ultimate correction technique

(*a*) IMEP, P_{IMEP}

	Average [kPa]	Standard deviation [kPa]	Fluctuation ratio [%]	Rate of reduction [%]
Condition 2	316	5.03	1.59	–
Condition 3	321	1.93	0.60	62.1

(*b*) Ultimate in-cylinder pressure, P_{max}

	Average [MPa]	Standard deviation [MPa]	Fluctuation ratio [%]	Rate of reduction [%]
Condition 2	2.45	0.20	8.24	–
Condition 3	2.70	0.11	4.02	51.2

(*c*) TDC pressure, P_{TDC}

	Average [MPa]	Standard deviation [MPa]	Fluctuation ratio [%]	Rate of reduction [%]
Condition 2	1.80	0.15	8.55	–
Condition 3	2.05	0.11	5.26	38.5

Figure 12 plots the distributions of probability density functions of the absolute difference values from the average IMEP, ΔP_{IMEP}, the averaged maximum in-cylinder pressure, ΔP_{max}, and the average TDC pressure, ΔP_{TDC}. For examining the ability of the average correction technique and the maximum correction technique, Figure 12 also shows the results obtained without the ignition timing control (under the condition 2 when using the standard ignition timing of 35 °CA before TDC). The term of ΔP_{IMEP} in Figure 12 represents the absolute difference values between the measured P_{IMEP} and the average P_{IMEP}, and the other two parameters were also evaluated here.

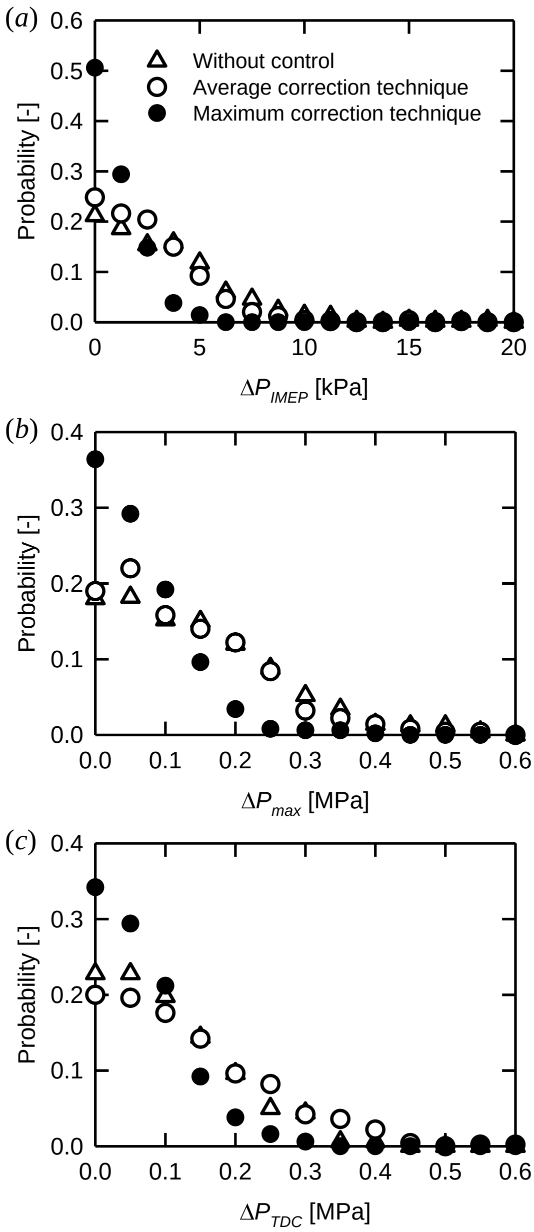

Figure 12. Distribution of probability density with function of absolute value of difference for (a) IMEP, (b) ultimate in-cylinder pressure, and (c) TDC pressure under condition 2 absence of control and condition 3 using control by utilizing both average correction technique and ultimate correction technique

The results shown in Figure 12 clearly indicated that the probabilities of ΔP_{IMEP}, ΔP_{max} and ΔP_{TDC} close to zero (thus, close to each average value) were increased by using the maximum correction technique, compared with the results using the average correction technique. This fact reveals that the fluctuation ratios of all three parameters were reduced, and thus, it was confirmed that the present developed method with the maximum correction technique had the advantage to reduce the combustion fluctuation.

5. Conclusions

For the reduction of the combustion fluctuation, this study suggested the approach to predict the TDC pressure in the next cycle and developed two types of methods to maintain a constant TDC pressure by controlling the ignition timing.

The ignition timing control by the average correction technique was found to reduce the fluctuation ratios of the IMEP and the maximum in-cylinder pressure by 22.7% and 15.9%, respectively. On the other hand, the fluctuation ratio of the TDC pressure was increased by 7.07%.

The ignition timing control by the maximum correction technique was found to reduce the fluctuation ratios of the IMEP, the maximum in-cylinder pressure, and the TDC pressure by 62.1%, 51.2%, and 38.5%, respectively. This result showed the effectiveness of this reduction method.

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