MBT Timing Detection and its Closed-Loop Control Using In-Cylinder Pressure Signal

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ABSTRACT

MBT timing for an internal combustion engine is also called minimum spark timing for best torque or the spark timing for maximum brake torque. Unless engine spark timing is limited by engine knock or emission requirements at a certain operational condition, there exists an MBT timing that yields the maximum work for a given air-to-fuel mixture. Traditionally, MBT timing for a particular engine is determined by conducting a spark sweep process that requires a substantial amount of time to obtain an MBT calibration. Recently, on-line MBT timing detection schemes have been proposed based upon cylinder pressure or ionization signals using peak cylinder pressure location, 50 percent fuel mass fraction burn location, pressure ratio, and so on. Because these criteria are solely based upon data correlation and observation, both of them may change at different engine operational conditions. Therefore, calibration is still required for each MBT detection scheme. This paper shows that MBT timing can be achieved by locating the maximum net pressure acceleration point at top dead center. This result is developed based upon the physical aspects of the combustion process, and therefore, it should be independent of engine operational conditions and valid for all spark-ignited engines that have one peak heat release rate during the combustion process. Experimental validation of this result over certain engine operational conditions is completed, and validation of this result over whole engine operational map is the subject of future work.

The second part of this paper develops an MBT timing closed-loop control using the detected MBT timing criteria as a feedback signal. The benefit of closed loop control of MBT timing is improved robustness over open-loop MBT timing calibration with respect to engine-to-engine variations, engine aging, engine operational conditions, etc. A two-way filtering algorithm, combined with the derivative calculation, is developed to improve the robustness of MBT timing detection scheme without the penalty of filter phase delay. A PI (proportional and integral) controller is used to illustrate closed-loop control of MBT timing, where the reference signal is used to control the engine ignition timing at its set point. The closed-loop control system is implemented in dSpace and prototyped on a two liter four cylinder engine. The test results show that the closed-loop MBT timing controller based upon the maximum net pressure acceleration point not only maintains the engine average ignition timing at its MBT timing but also reduces the cycle-to-cycle variations. For comparison purpose, three MBT timing feedback signals are used in the study: peak cylinder pressure location, 50 percent burn location, and maximum net pressure acceleration location.

INTRODUCTION

Traditionally, MBT timing is determined by conducting a spark timing sweep. Almost every calibration point needs a spark sweep to see if the engine can be operated at the MBT timing condition. If not, a certain degree of safety margin is needed to avoid pre-ignition or knock during engine operation. Open-loop spark mapping usually requires a tremendous amount of effort and time to achieve a satisfactory calibration.

In recent years, various closed loop spark timing control schemes have been proposed based upon cylinder pressure measurements [1,3,5-8] or spark ionization sensing [9]. Based on test data, it has been found that the peak cylinder pressure usually occurs around 15 °ATDC at MBT timing. The 50% mass fraction burned point generally occurs from 8 to 10 °ATDC when MBT timing is achieved, see [4]. The algorithm published in [3] controls PR(10) (normalized pressure ratio of incylinder and motoring pressure at 10 °ATDC) around 0.55 to obtain the MBT timing. Because these criteria are solely based upon observations and may change at different operating conditions, each algorithm still requires some calibration effort. It is clear that the combustion process has to be matched with the engine cylinder volume change to attain the best torque. However, there is no sound theory to support the rational that peak cylinder pressure must occur around 15 °ATDC or that 50% burned must happen around 9 °ATDC for the MBT timing conditions.
physical limitations, etc. For this paper, we concentrated misfire and knock spark timing limits, as well as engine The desired engine spark timing is a function of MBT, fraction burned (MAMFB) is developed and validated. obtaining best torque. In this paper, an MBT timing ignition of the mixture on time, the heat release process would not be to the heat release before the Top Dead Center (TDC) would generate negative work. If one doesn’t ignite the mixture too soon, the pressure increase due at TDC. Therefore, the decision on where to ignite the combustion process slows down and attains its maximum deceleration point. Because the combustion cannot complete instantaneously and the chamber volume is constantly changing, choice of alignment of these critical points versus crank angle may have significant impact on how much useful work can be accomplished during the combustion process. If one ignites the mixture too soon, the pressure increase due to the heat release before the Top Dead Center (TDC) would generate negative work. If one doesn’t ignite the mixture on time, the heat release process would not be efficient enough to utilize the small volume advantages at TDC. Therefore, the decision on where to ignite the combustion mixture becomes a critical factor of obtaining best torque. In this paper, an MBT timing criterion based upon maximum acceleration of mass fraction burned (MAMFB) is developed and validated. The key event associated with the combustion process begins with the spark event. After the spark discharge, the flame kernel starts to form. Once the flame kernel becomes stable, it develops very fast and the combustion process reaches its maximum acceleration point. Then the rapid burning period starts and reaches its maximum heat release velocity very quickly. After this point, the combustion process slows down and attains its maximum deceleration point. Because the combustion cannot complete instantaneously and the chamber volume is constantly changing, choice of alignment of these critical points versus crank angle may have significant impact on how much useful work can be accomplished during the combustion process. If one ignites the mixture too soon, the pressure increase due to the heat release before the Top Dead Center (TDC) would generate negative work. If one doesn’t ignite the mixture on time, the heat release process would not be efficient enough to utilize the small volume advantages at TDC. Therefore, the decision on where to ignite the combustion mixture becomes a critical factor of obtaining best torque. In this paper, an MBT timing criterion based upon maximum acceleration of mass fraction burned (MAMFB) is developed and validated. The desired engine spark timing is a function of MBT, misfire and knock spark timing limits, as well as engine physical limitations, etc. For this paper, we concentrated mainly on closed-loop MBT spark timing controller development. For the closed-loop MBT timing control strategy, individual cylinder pressure was sampled at every crank degree and processed every combustion event to generate both MBT timing criterion and closed-loop MBT timing control output. The final spark time in oBTDC (Degrees Before Top Dead Center) was limited by both advance and retard bounds that were dynamically modified by both misfire and knock limit managers. The closed-loop MBT timing control strategies were validated using a two-liter four-cylinder engine in a dynamometer located at the Visteon Dearborn Technical Center. A dSpace expansion box was used for controlling engine spark timing in closed-loop and the dynamometer controller controls engine speed, load, fueling, EGR, etc. The closed-loop MBT spark control was demonstrated using three feedback control criteria: peak cylinder pressure (PCP) location, 50% mass fuel burn (MFB50%) location, and maximum acceleration location of mass fraction burn (MAMFB). Test results show stable MBT timing control for all three closed-loop control strategies (PCP, MFB50%, and MAMFB) in both transient and steady state operation. The MBT spark timing was achieved over the complete engine operational map when MAMFB remains at zero, while MFB50% and PCP locations varies within several crank degrees over engine map when MBT spark is achieved.

**MBT TIMING DETECTION**

The mass fraction burned is mostly determined by the well-known Rassweiler-Withrow [2] method established in 1938 through pressure measurement. It uses the chamber volume at the ignition as a reference and calculates the net pressure increase at every crank angle for the whole combustion process, then normalizes the pressure by the maximum pressure increase at the end of combustion. The procedure ignores the heat loss and mixture leakage during the combustion. Each percentage of pressure increase signifies the percentage of mass fraction of fuel burned at the corresponding crank angle.

The closed-loop MBT spark control was demonstrated using three feedback control criteria: peak cylinder pressure (PCP) location, 50% mass fuel burn (MFB50%) location, and maximum acceleration location of mass fraction burn (MAMFB). Test results show stable MBT timing control for all three closed-loop control strategies (PCP, MFB50%, and MAMFB) in both transient and steady state operation. The MBT spark timing was achieved over the complete engine operational map when MAMFB remains at zero, while MFB50% and PCP locations varies within several crank degrees over engine map when MBT spark is achieved.

In this study, instead of using the mass fraction burned, we used the net pressure $P$ and its first and second derivatives to represent the distance, velocity and acceleration of the combustion process. If we normalize the net pressure by the overall net pressure increase at the end of the combustion, the result is mass fraction burned. Note that the pressure difference $P(i+1)-P(i)$, where $i$ represents the current crank angle, is caused by two parts. One is the pressure change due to volume change that can be found through the difference $P(i)^*\left(V(i)/V(i+1)\right)^{1.3} = P(i)$, assuming the pressure undergoes isentropic compression or expansion. The other is the pressure difference resulting from combustion between two crank angles that can be represented by $P(i+1) - P(i)^*\left(V(i)/V(i+1)\right)^{1.3}$, that is evaluated at volume $V(i)$. In order to know the net pressure without any volume change since the ignition,
the difference should be compared with the volume at the ignition point as if the combustion undergoes constant volume combustion. Therefore, the net pressure change between two crank angles is:

\[
\Delta P(i) = \left( P(i+1) - P(i) \right) \left( \frac{V(i)}{V(i+1)} \right) \left( \frac{V(i)}{V_{ig}} \right)^{1.5} \quad \text{(Eq. 1)}
\]

and the net pressure at each crank angle is

\[
P_{\text{NET}}(i) = P_{\text{NET}}(i-1) + \Delta P(i), \quad \text{(Eq. 2)}
\]

where \( P \) is pressure, \( V \) is volume and \( V_{ig} \) is the chamber volume at the ignition point.

Figure 2 shows engine torque output at different spark timing when operating at 2500 RPM with 7.86 bar BMEP, and Figure 3 shows the corresponding pressure acceleration curves with different spark timing. The calculation is based upon the average pressure signal over 300 combustion cycles. It is clear from Figure 2 that the MBT timing occurs around 28° BTDC. The peak acceleration points shown in Figure 3 gradually advances as the spark timing advances. At 28° BTDC, the peak acceleration of pressure is located very close to TDC. Based on Figure 3, at 28 BTDC, the pressure velocity reaches its maximum at about 9° ATDC and the net pressure at this point is about 50% of the total net pressure. As we have mentioned earlier, locating 50% mass fraction burned at 9° ATDC is often used as an indicator for MBT timing.

After the maximum pressure acceleration is reached, the crank angle taken for the flame propagating to the peak velocity point is mainly determined by the flame speed, see Figure 4. When the fuel is leaner or EGR rate is higher, the flame speed will be slower. Therefore, it will take a longer time for the flame to propagate and the peak pressure velocity point will occur later. At low load conditions, because the pressure and temperature are relatively lower, the flame speed is also slower and the peak velocity point happens later. As the engine speed increases, the turbulence becomes stronger and the flame speed is faster, and the peak pressure velocity point occurs slightly earlier.

Figure 5 shows the BMEP changes with the spark timing when the engine operates at 1500 RPM with 2.62 bar BMEP and different EGR rates for the two-liter four-cylinder engine. The MBT timing can be found for each EGR condition. Figure 6 shows the acceleration curves at different EGR rates. The spark timing at each condition associated with the maximum acceleration point locating at TDC and the spark timings found through torque measurement are listed in Table I.
Test data has shown that MBT timing occurs when the maximum net pressure acceleration point is located at TDC. The question is: is this phenomenon only true for several operating conditions or is it true for all operating conditions? As mentioned before, the combustion process has its distinctive footprint that is signified by the mass fraction burned. The whole combustion process can be compared to a distance runner entering a race. Deciding where to attain maximum acceleration and when and where to reach peak velocity will determine how well the runner finishes in the race. It is well known that the work generated before the top dead center (TDC) is wasted in a fight with the moving piston and produces heat. However, it is a necessary step for the flame to establish itself for further flame development. The useful work is done after TDC. If we go back to Figure 1, we can see that the combustion process reaches its maximum acceleration point at a relatively early stage, which indicates that the early flame preparation is finished at this point and the combustion is ready to start the rapid burning period. If we achieve this maximum acceleration point before TDC, some of the rapid burning period will be wasted before the TDC. If we attain the maximum acceleration point after the TDC, the rapid burning period right after the maximum acceleration point will result in lower combustion efficiency. Therefore, it is reasonable to start the rapid burning period right at the top dead center, which maximizes the useful work. In other words, when the spark timing is advanced to the point where the maximum acceleration point aligns with the top dead center, we can obtain the most useful work out of the combustion process and we achieve MBT timing.

In Figure 7, acceleration curves for all four cylinders are plotted for the two-liter four-cylinder engine operated at 3000 RPM with 7 bar BMEP. The IMEP reading for cylinder one starts to drop at spark timing 24 °BTDC, while the rest of the cylinders have not reached the maximum IMEP. Therefore, setting the spark timing for all cylinders at 24 °BTDC will limit the maximum torque that can be delivered from the engine. Since cylinder one starts to experience some minor knock, it would be ideal for this cylinder to have later spark timing than the rest of the cylinders, and the rest of the cylinders can have slightly advanced spark timing to achieve the maximum torque.
process of the combustion does not change, the interaction between the combustion energy release and the cylinder volume change will still be the same. For a gasoline direct injection engine, if the multiple injection schemes are not adopted, lining up the peak acceleration point at the TDC will still yield the MBT timing. However, this hypothesis needs to be validated with the help of extensive test data.

It is also worth mentioning that the method of finding MBT timing developed in this study should be coupled with knock detection to yield the best and safest spark timing for the engine operation.

**AN MBT DETECTION ALGORITHM**

In order to implement the MBT detection criterion using the location of maximum acceleration (MAMFB), a detection algorithm was developed. The MBT detection algorithm can be divided into the following steps.

**Step 1: Net Pressure Calculation**

Net pressure is calculated based upon the sampled pressure signal during engine compression and expansion stroke, using the formulae defined in (Eq. 1) and (Eq. 2). The purpose of using net pressure instead of actual pressure is to exclude pressure variation due to piston compression and expansion. A typical net pressure curve can be found in Figure 4.

It is worth mentioning that the calculated net pressure can be used to calculate mass fraction burned location. For instance, 50% burn location can be found by detecting the crank-angle when net pressure rises to 50% of its peak during compression and expansion strokes.

**Step 2: Double net pressure derivative calculation**

Net pressure points between 15 °BTDC and 15 °ATDC are used to calculate the double net pressure derivative. Due to the fact that derivative operation is very sensitive to noise, a special filtering technique, called two-way low pass filtering, is used along with the derivative calculation. The off-line calculation between combustion events makes it possible. A key factor in using this filtering technique for double derivative calculation is minimization of the phase shift, which is directly associated with the accuracy of MBT timing detection. The first derivative (difference) is calculated using the following transfer function,

\[
\frac{dP_{net}(z)}{P_{net}(z)} = F_g(z) \cdot F_d(z) \cdot D(z)
\]

where \( a \) is the digital filter parameter associated with the low pass filter bandwidth, and \( F_g(z), F_d(z), \) and \( D(z) \) are first order backward, first order forward, and first order difference transfer functions, respectively. Note that the complete transfer function can be rewritten as follows,
The Bode plot of the two-way filtering transfer function

\[ \frac{dP_{NET}(z)}{P_{NET}(z)} = \frac{(1-a)^2 \cdot (1-z^{-1})}{(1+a^2) - a(z+z^{-1})}. \]  
(Eq. 4)

Similarly, the second derivative is defined as follows,

\[ \frac{d^2 P_{NET}(z)}{dP_{NET}(z)} = F_f(z) \cdot F_f(z) \cdot D(z) \]  
(Eq. 5)

\[ = \frac{1-a}{1-a \cdot z} \cdot \frac{1-a}{1-a \cdot z} \cdot \frac{(1-a)^2}{(1+a^2) - a(z+z^{-1})}. \]

Note that the discrete transfer function of the two-way low pass filtering algorithm can be lumped together as follows,

\[ G_f(z) = \frac{1-a}{1-a \cdot z} \cdot \frac{1-a}{1-a \cdot z} = \frac{(1-a)^2}{(1+a^2) - a(z+z^{-1})}. \]  
(Eq. 6)

The Bode plot of the two-way filtering transfer function \( F_f(z)F_f(z) \) is shown in Figure 9. It is clear that the first order two-way filter is equivalent to a second order filter without phase delay. Also notice that the two-way filter is anti-causal (i.e., it cannot be realized in real time since the back filter uses future information), and the combined two-way filtering transfer function cannot be used directly since it is an unstable filter transfer function (one is inside the unit circle and one is outside the unit circle, i.e., \( a \) and \( a^{-1} \)). The two-way filter defined in (Eq. 6) can only be realized off-line to ensure a stable filtering calculation, that is, filtering the raw signal using the first order stable forward filter \( F_f(z) \) defined in (Eq. 3), reversing the order of the filtered signal, and then filtering the reversed-order signal using the same forward filter to have a stable backward filter. The last two steps guarantee the numerical stability of backward filtering.

For comparison purpose, two other MBT timing criteria are used for closed-loop spark time control in this study. They are 50% burn location (MFB50%) and Peak Cylinder Pressure (PCP) location.

### CONTROL ARCHITECTURE AND STRATEGY

The purpose of closed-loop MBT timing control is two-fold: keeping the engine running at its MBT spark timing, if it is not knock limited, and reducing the cycle-to-cycle combustion variation through closed-loop spark timing control. The closed-loop control architecture of MBT timing is limited by knock constraints within engine controller. Instead of controlling engine spark timing using calibrated tables as function of engine speed, load, etc., an engine ignition timing control is generated by a closed-loop PI (Proportional and Integral) controller using information derived from in-cylinder pressure as the feedback signal.

In the rest of this paper, "closed-loop MAMFB MBT timing controller" refers to the closed-loop MBT timing controller using Maximum Acceleration location of Mass Fraction Burned (MAMFB). "Closed-loop PCP MBT timing controller" refers to the closed loop controller using PCP location, and "closed-loop MFB50% MBT timing controller" refers to the closed loop controller using 50% mass fraction burned (MFB50%). The results of the three closed loop MBT timing controllers (MAMFB, PCP, and MFB50%) will be compared.

![Closed-loop MBT timing control architecture](image)

**Figure 10 Closed-loop MBT timing control architecture**

The inputs to the closed-loop MBT timing controller are the individual in-cylinder pressure signals, the conditioned knock intensity signal, and the current engine operational information such as the engine speed, load, etc., see Figure 10.

**Cylinder pressure vector:**

The individual cylinder pressure signal is sampled at a one crank degree resolution for all cylinders. Only the compression and expansion cycles of the in-cylinder pressures are sampled. The sampled cylinder pressure signal is available for closed-loop control right after engine expansion stroke for each corresponding cylinder.

**Step 3: MAMFB location calculation:**

After the double derivative is calculated using the two-way filter technique, the MAMFB location can be found by locating the maximum over the double derivative signal.
Conditioned knock intensity:
The knock intensity is calculated using cylinder pressure signal over a specific window, typically right after the peak cylinder pressure location. The pressure signal over the knock window is filtered by a bandpass filter, and then integrated using absolute value of the bandpass filtered signal. Because knock frequency is relatively high compared with one crank degree sampling resolution at low engine speed, the knock intensity is obtained through an analog circuit.

Engine speed and load:
Engine speed and load are lookup table inputs for setting hard timing advance and retard limits for advance and retard limit managers, see Figure 10.

For closed-loop MAMFB MBT timing control, the MBT estimation block in Figure 10 calculates the engine net pressure based upon (Eq. 1) and (Eq. 2). The calculated net pressure is differentiated twice using (Eq. 3) and (Eq. 4). Note that forward and backward filtering techniques are used to reduce noise with minimal filtering phase shift. Finally, the crank angle associated with the maximum acceleration location of the net pressure or mass fraction burned (also called MAMFB) is calculated as the MBT feedback signal. For closed-loop PCP MBT timing control, peak cylinder pressure location is detected and used as the MBT feedback signal, and for MFB50% control, 50% MFB location is used as the MBT feedback signal.

The MBT estimation block also calculates the misfire index using the calculated net pressure. Misfire of the corresponding cylinder is declared if the net pressure is below a threshold as a function of engine speed and load. The knock index is determined using the knock intensity input. Both advance and retard limit managers use the engine knock and misfire index, obtained from the MBT estimation block, to generate both advance and retard timing bounds.

The closed-loop spark MBT timing control is realized using a PI (Proportional and Integral) controller. The error between MBT reference and the MBT feedback signal is used as an input to the PI controller. The MBT reference signal is a function of MBT timing control method being tested. For MAMFB approach, the MBT reference is zero, for PCP approach, MBT reference is around 15 °ATDC, and for 50% MFB approach, around 9 °ATDC.

The limit management block passes through the desired ignition timing from PI controller if the signal is within the advance and retard limits. Otherwise, the output of the PI controller will be saturated by either the advance or retard spark timing limit.

TEST CONFIGURATION

The closed-loop MBT timing controller was validated in an engine dynamometer. A two-liter four-cylinder engine was used for the validation test. The four-cylinder engine was controlled by the dynamometer controller except for engine spark timing. All engine sensors were connected to the dynamometer controller. The dynamometer controller controlled the engine throttle position, EGR rate, and fuel injection. It also controlled the engine speed and load. A dSpace PX-10 expansion box was used for both open-loop and closed-loop spark timing control. Kistler pressure sensors were installed in every cylinder for estimating MBT criterion used for closed-loop feedback control.

The dSpace PX-10 expansion box, used for closed loop MBT timing control, consists of a main processor card, a fast A/D card, a digital waveform capture card, and a digital waveform output card.

The digital waveform capture card generates the interrupt based upon the crankshaft encoder pulse, that triggers the data sampling process. The interrupt also calculates current crank angle, synchronized by the camshaft sensor, to arrange the sampled pressure signal into an array during compression and expansion cycle of the corresponding cylinder. The crank angle also generates software interrupt to enable combustion event-based closed-loop spark control calculation.

The dSpace data sampling and control scheme is event-based. The cylinder pressure signals are sampled every crank-degree and the spark timing command is calculated during exhaust stroke of the corresponding cylinder to make sure that the spark control commands are available at intake stroke for corresponding cylinder.

As a summary, two crank-based processes are running in the dSpace main processor. The first runs every crank angle that is triggered by crankshaft encoder, and the second runs every 180 crank degrees (for a four cylinder engine) that is triggered by the first crank based process through software interrupt. The first process has a higher priority than the second one so that the data sampling and current crank angle calculation is guaranteed.

As mentioned before, the first process samples individual cylinder pressure signals and arranges them into a data array using compression and expansion stroke data. The other main task is to send digital ignition signal through the digital waveform output card based upon the ignition command generated by the closed-loop MBT timing control algorithm during the second process.

The second dSpace process runs the closed-loop MBT timing control strategy. For the two-liter four-cylinder engine used for control concept validation, the closed-loop MBT timing control algorithm, shown in Figure 10, runs every 180 crank degrees.

The closed-loop MBT timing control strategy shown in Figure 10 is implemented in Simulink environment utilizing the dSpace hardware. The closed-loop MBT
Timing control strategy implemented in Simulink allows controlling the MBT timing using three MBT timing criteria as feedback signals. They are MAMFB, PCP, and MFB50%. The purpose is to compare the test results of the three closed-loop control approaches.

**TEST RESULTS AND ANALYSIS**

Before the closed-loop MBT timing control is evaluated, the MAMFB MBT timing estimation is validated in dynamometer tests. Figure 11 shows the three MBT timing criteria with open-loop (or fixed) engine spark timing control. The engine was running at 1500 RPM with 34.5 NM load. The data shown in Figure 11 is 100 cycles of data for cylinder three only. It is obvious that the engine is not running at its MBT timing since all three MBT timing criteria show that the engine is almost three degrees advanced from its MBT timing. For example, the mean PCP location is around three degree ahead from its MBT timing location (15 °ATDC). The ranges of three MBT timing criteria (PCP, MFB50%, and MAMFB) vary over a 12 degree window for the 100 engine cycle data shown in Figure 11.

Figure 12 shows the responses of three MBT timing criteria (PCP top line with "o", MFB50% middle line with "Δ", and MAMFB bottom line with "◆") when the engine ignition timing is controlled in a closed-loop manor using MAMFB MBT timing criterion as feedback signal. Both proportional and integral gains are set to 0.2. The engine operation condition is the same as the open-loop control case shown in Figure 11. It is clear that that with the help of the closed-loop MBT timing control, the engine operates at its MBT timing. This can be validated by checking three MBT timing criteria shown in Figure 12. The mean of three MBT timing criteria are 14.9, 9.14, and 0 for PCP, MFB50%, and MAMFB locations, respectively. That is close to desired location for all three MBT timing criteria (PCP 15 °ATDC, MFB50% 9 °ATDC, and MAMFB 0 °ATDC).

Through observation of Figure 11 it is clear that three MBT criteria are highly correlated. That is, when one MBT timing criterion moves in an advance direction, the other two follow. Table 2 shows the correlation matrices of PCP, MFB50%, and MAMFB for all four cylinders. It is clear that the highest correlation is between the PCP and MFB50% for all cylinders (0.9716, 0.9589, 0.9535, and 0.9753 for cylinders one to four), and MAMFB location has higher correlation to MFB50% location (0.8920, 0.8926, 0.8798, and 0.9373) than PCP location (0.8554, 0.8368, 0.7863, and 0.9018) for all four cylinders. This implies that there is no significant difference between MBT timing criteria PCP and MFB50% locations and MAMFB criterion is less correlated with the PCP and MFB50% criteria.

Closed-loop MBT timing control using the other two MBT timing criteria PCP and MFB50% locations were also conducted and similar response to Figure 12 were obtained. The main difference is that the MBT reference for MAMFB approach remains constant at zero for all engine operational conditions, while the references for the other two feedback criteria (PCP and MFB50% locations) have to be adjusted for the test engine to operate at its MBT timing over the whole engine speed and load range.

Another aspect of analyzing closed-loop control of engine MBT timing is from a stochastic perspective. It is well known that for a linear system with a stationary stochastic process input, closed-loop controllers, such as an LQG (Linear Quadratic Gaussian) controller, are able to reduce system output variances. Figure 13 shows output variances of three MBT timing criteria for both open-loop and closed-loop system using MAMFB control. The engine operation condition is the same as...
the open-loop control case shown in Figure 11. It is clear that closed-loop control using MAMFB MBT timing criterion reduces all three MBT timing criteria variances shown in Figure 13. One conclusion from Figure 13 is that closed-loop MAMFB MBT timing control reduces variances of PCP, MFB50%, and MAMFB locations, hence, reduces combustion cycle-to-cycle variation.

The same variances of three MBT timing criteria are shown in Figure 14 for the case of closed-loop PCP MBT timing control when the engine was operated at the same condition as the closed-loop MAMFB MBT timing control case shown in Figure 13 with the selected PI control gains equal to half of MAMFB ones. It is clear that the variance improvement is not uniform, compared to the case of closed-loop MAMFB MBT timing control.

Figure 15 shows the same variances of three MBT timing criteria for the case of closed-loop MFB50% MBT timing control when the engine was operated at the same condition as the closed-loop MAMFB MBT timing control case shown in Figure 13 with the same PI control gain as MAMFB case. Similar to the case of closed-loop PCP MBT timing control, the variance improvement of MBT criteria is not uniform.

Recall that, as illustrated in the correlation matrices of Table 2, the MBT timing criteria PCP and MFB50% locations have very high correlations (above 0.9535) for all cylinders. It is not surprising that the performance of both PCP and MFB50% MBT timing control is similar in stochastic sense.

The transient performance of closed-loop MBT timing control was also studied. Figure 16 and Figure 17 show the results of closed-loop MAMFB MBT timing control during engine warm up process. The engine was running at 2000 RPM with 44 NM load. The whole
process lasted for about 10 minutes and resulted in ten thousand engine cycles. The starting engine coolant temperature is about 34 °C and the ending temperature is about 78 °C. The top graphs of both Figure 16 and Figure 17 show the relationship between engine coolant temperature and engine MBT timing. In order to keep the maximum acceleration location of mass fuel burned at around TDC location, the ignition timing has to be advanced to compensate relatively slow burn when engine is cold. It is clear that during the ten-minute warm-up process, the MBT timing controller moves the spark timing in a retard direction from around 37 °BTDC to 32 °BTDC. During this warm up process, the burn-rate increases and the corresponding MBT spark timing moves back in a retard direction.

The five graphs below the top one of both Figure 16 and Figure 17 validate that engine operates at its MBT timing. Figure 16 shows both individual PCP location and mean PCP locations of all four cylinders. The second graph from top shows the mean MFB50% location of four cylinders, and the third to sixth graphs from top shows the MFB50% locations for cylinders one through four, respectively. The mean value of MFB50% MBT criterion stays around 10 °ATDC, indicating that engine was operating at its MBT timing during the transition. This shows that closed-loop MBT timing control can be used to compensate the MBT timing change during engine warm up process.

**CONCLUSIONS**

A new MBT timing criterion is developed using the maximum acceleration location of mass fraction burned, which is independent of the engine speed and load. The concept has been validated over certain engine operational range. The potential benefit of using this new MBT criterion for closed-loop control is reduced calibration and a reduced cycle-to-cycle variation. An MBT timing detection algorithm is also developed specially to handle the double derivatives required for calculating the newly developed MBT timing criterion (MAMFB). The special two-way (forward and backward) filtering algorithm, combined with double derivative calculation, improves numerical stability of the MBT timing estimation algorithm.

Closed-loop MBT timing control were evaluated using three different MBT timing criteria PCP, MFB50%, and MAMFB locations. The engine ignition timing remains at its MBT location when the engine is operated at the steady condition for all three closed-loop controllers. During engine warm up process, the closed-loop MAMFB MBT timing controller keeps the engine operated at its MBT timing. At the same time engine MBT timing moves at the retard direction while the engine coolant temperature increases.

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Bruce Wang implemented closed-loop MBT timing control strategy into dSpace and made dynamometer engine tests possible.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

MBT: Minimum spark advance for Best Torque
TDC: Top Dead Center
°ATDC: Degrees After Top Dead Center
°BTDC: Degrees Before Top Dead Center
PRM: Pressure Ratio Management
MFB: Mass Fraction Burned
BMEP: Brake specific Mean Effective Pressure
IMEP: Indicated Mean Effective Pressure
EGR: Exhaust Gas Recirculation
PFI: Port Fuel Injection
GDI: Gasoline Direct Injection
PCP: Peak Cylinder Pressure
MFB50%: 50% Mass Fraction Burned
MAMFB: Maximum Acceleration of Mass Fraction Burned
PI: Proportional and Integral
A/D: Analog to Digital
NM: Newton Meter
LQG: Linear Quadratic Gaussian