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

Guoming G. Zhu, Chao F. Daniels and Jim Winkelman
Visteon Corporation

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ABSTRACT

Maximum Brake Torque (MBT) timing for an internal combustion engine is the minimum advance of spark timing for best torque. Traditionally, MBT timing is an open loop feedforward control whose values are experimentally determined by conducting spark sweeps at different speed, load points and at different environmental operating conditions. 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. This paper shows that MBT timing can be achieved by regulating a composite feedback measure derived from the in-cylinder ionization signal referenced to a top dead center crank angle position. A PI (proportional and integral) controller is used to illustrate closed-loop control of MBT timing. The test results show that the control, using the ionization current based feedback signal, not only maintains the engine average ignition timing at its MBT timing but also reduces the cycle-to-cycle variations.

INTRODUCTION

Traditionally, internal combustion MBT (Maximum Brake Torque) timing is determined by conducting a spark 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], [2], [3], [4], [5], [6], [7], and [12]) or spark ionization sensing ([8] and [9]). Based on test data, it has been found that the peak cylinder pressure usually occurs around 15° ATDC (After Top Dead Center) at MBT timing. The 50 percent mass fraction burned point generally occurs between 8° and 10° ATDC when MBT timing is achieved, see [10]. The algorithm published in [3] controls PR(10) (normalized Pressure Ratio of in-cylinder 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.

This paper proposed a real-time estimation algorithm, using ionization signal, to construct a composite MBT timing criterion that is robust over engine operational map. The proposed MBT timing estimation algorithm is validated with dynamometer tests. The MBT information using in-cylinder ionization signal is discussed in reference [11], where PCP (Peak Cylinder Pressure) location, 10 and 50 percent Mass Fraction Burned (MFB) locations are correlated to the specific locations of the corresponding ionization signal.

Closed-loop MBT timing control using in-cylinder pressure feedback was described in [5] and [12], and closed-loop ignition timing control was presented in [9]. This paper mainly describes closed-loop MBT spark timing controller development, using the composite ionization MBT criterion as feedback signal. For the closed-loop MBT timing control strategy, an individual cylinder ionization signal was sampled at every crank degree and processed every combustion event to generate both composite MBT timing feedback criterion and closed-loop MBT timing control output. The final spark timing in DATDC (Degrees After Top Dead Center) was limited by both advance and retard spark timing bounds that were dynamically modified by both misfire and knock limit managers. The closed-loop MBT timing control strategy was validated using a two-liter...
Four-cylinder engine in a dynamometer. A dSpace expansion box was used for controlling engine spark timing closed-loop and the engine dynamometer controls engine speed, load, fueling, EGR (Exhaust Gas Recirculation), etc. Test results show stable MBT timing control for both steady state and slow transient operation conditions.

FULL RANGE MBT TIMING DETECTION USING IONIZATION MEASUREMENTS

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. In reference [12], instead of directly using MFB, connection between MFB and net pressure is utilized to simplify analysis. The net pressure $P_{NET}$ and its first and second derivatives are used to represent the distance, velocity and acceleration of the combustion process. References [10] and [12] show that PCP location, 50 percent MBF location, and maximum acceleration location of the net pressure can be used as MBT timing criteria for closed-loop control, respectively. In the rest of this section, a composite MBT timing criterion is developed and validated through engine dynamometer test.

The combustion process of an internal combustion engine is usually described using the mass fraction burned versus crank angle. Through mass fraction burned, one can find when the combustion has its peak burning velocity and acceleration and percentage burn location as a function of crank angle. Maintaining these critical events at a specific crank angle produces the most efficient combustion process. In other words, the MBT timing can be found through these critical events. As described in [11], the inflection point right after the first peak (called the first inflection point, see Figure 1) can be correlated to the maximum acceleration point of the net pressure and this point is usually between 10% to 15% mass fraction burned. The inflection point right before the second peak of the ionization signal (called the second inflection point, see Figure 1) correlates well with the maximum heat release point and locates right around 50% mass fraction burned location. In addition, the second peak location is related to the peak pressure location of the pressure signal, see Figure 1.

As described in references [10] and [12], at MBT timing, the Maximum Acceleration point of Mass Fraction Burned (MAMFB) is located at around TDC; the 50 percent Mass Fraction Burned location (50%MFB) is between 8° and 10° ATDC; and the peak cylinder pressure location (PCPL) around 15° ATDC. Using the MBT timing criteria relationship between in-cylinder pressure and in-cylinder ionization signal, these three MBT timing criteria (MAMFB, 50%MFB, and PCPL) can be obtained using an in-cylinder ionization signal.

It is well known that the second peak of the ionization signal is mainly due to the in-cylinder temperature rise during the combustion process. In the case that in-cylinder temperature does not reach a re-ionization temperature threshold, the second peak of the ionization signal may disappear. For example, when the engine is operated either at the idle condition, with very high EGR rate or with lean air to fuel (A/F) mixture or combination of the above, the flame temperature is relatively low and the temperature could be below the re-ionization temperature threshold. Therefore, the second peak may not be shown in the ionization signal. As a summary, at various engine operational conditions, in-cylinder

Figure 1 shows a typical ionization signal versus crank angle, where 0° is Top Dead Center (TDC), and the corresponding in-cylinder pressure signal. Different from an in-cylinder pressure signal, an ionization signal actually shows more detailed information about the combustion process through its waveform. It shows when a flame kernel is formed and propagates away from the gap, when the combustion is accelerating rapidly, when the combustion reaches its peak burning rate, and when the combustion ends. A typical ionization signal usually consists of two peaks. The first peak of the ion signal represents the flame kernel growth and development, and the second peak is the re-ionization due to the in-cylinder temperature increase resulted from both pressure increase and flame development in the cylinder.
The ionization signal waveform can be divided into the following three cases.

**Case 1:** Normal ionization waveform: both peaks are presented in the waveform.
**Case 2:** The first peak ionization signal: low combustion temperature resulting in no second peak.
**Case 3:** The second peak ionization signal: high engine speed such that the first peak merges with the ignition signal due to the longer ignition duration as a result of a relatively constant spark duration at high engine speed.

![Figure 2 Three cases of ionization waveforms](image)

**Figure 2** shows these three cases. For case 1 the engine was operated at 1500 RPM with 2.62 bar BMEP (Brake Mean Effective Pressure) load and without EGR, for case 2 the engine was running at the same condition as case 1 except with 15% EGR, and for case 3 the engine was running at 3500 RPM with wide open throttle.

It is clear from Figure 2 that three MBT timing criteria (MAMFB, 50%MFB, and PCPL) are available only in case one, and for cases two and three, only one or two criteria is available. This indicates that at some operating conditions, only one or two MBT timing criteria can be obtained for estimating MBT timing. The proposed MBT timing estimation method is to combine all MBT timing criteria available at current operational condition into one single composite criterion for improved reliability and robustness. The detailed algorithm is described in next section.

**AN MBT TIMING DETECTION ALGORITHM**

In order to implement the MBT timing estimation strategy using an in-cylinder ionization signal, a detection algorithm was developed. The MBT detection algorithm can be divided into the following steps.

**Step 1: Ionization signal conditioning**

For each cylinder, the ionization signal is sampled at every crank degree after the ignition coil dwell event for 120 degrees, as the ionization signal disappears after 120 crank angle degrees. The sampled ionization signal $ION$ is conditioned by a low pass filtering to improve the accuracy of detecting the first and second peaks and inflection points. In order to minimize the phase shift due to low pass filtering for improved MBT timing estimation, a two-way low pass filtering technique is used [12]. The off-line calculation between combustion events allows this non-causal calculation. The two-way low pass filter has the following transfer function,

$$
\frac{ION_{\text{COND}}(z)}{ION(z)} = \frac{1 - a z^{-1}}{1 - a z^{-1}}
$$

(Eq. 1)

where $a$ is the digital filter parameter associated with the low pass filter bandwidth, and $F_B(z)$ and $F_F(z)$ are first order backward and first order forward filter transfer functions, respectively. Note that the combined transfer function can be rewritten as follows,

$$
\frac{ION_{\text{COND}}(z)}{ION(z)} = \frac{(1 - a)^2}{(1 + a^2) - a(z + z^{-1})}.
$$

(Eq. 2)

For the experiments conducted, 0.9 was selected for $a$, which is corresponding to 300 Hz bandwidth when the engine is operated at 1500 RPM.

**Step 2: Operational condition identification**

In this step, engine operational condition is identified, and the resulting output of this step is which case the sampled ionization signal belongs to, that is case 1, 2 or 3.

**Step 3: MBT timing criteria calculation**

After the ionization signal case is identified, MBT timing criteria can be calculated using a peak location detection algorithm. The inflection location detection logic can be implemented by applying a peak location detection algorithm to the derivative of the filtered ionization signal.

**Step 4: Composite MBT timing criterion generation**

The composite MBT timing criterion is calculated based upon the availability of the MBT timing criteria calculated from the in-cylinder ionization signal.

For Case 1, since all three MBT timing criteria are available, the composite MBT timing criterion can be calculated using the following equation.
Since the composite MBT timing criterion equals to zero when engine is running at its MBT timing condition, MBT timing criteria 50%MFB and PCPL needs to be shifted from their nominal location defined by 50%\textit{BURNOFFSET} and PCPL_{OFFSET}, respectively. 50%\textit{MFBOFFSET} and PCPL_{OFFSET} are around 8° to 10° and 14° to 16° ATDC, respectively when the engine is operated at its MBT timing. Since both 50%\textit{MFBOFFSET} and PCPL_{OFFSET} varies as a function of engine operational conditions (a few degrees), it is proposed to make them as a function of engine operational conditions such as engine speed, load, etc. Coefficients \( \alpha_{\text{MAMFB}} \), \( \alpha_{\text{50%MFB}} \), and \( \alpha_{\text{50%MFB}} \) equal to either zero or one and are used to enable or disable the corresponding MBT timing criterion to be used for calculating the composite MBT timing criterion.

For Case 2, the only MBT timing criterion available is MAMFB, therefore, it is used for calculation composite MBT timing criterion as follows

\[
C_{\text{MBT}} = MAMFB \quad \text{(Eq. 3)}
\]

For Case 3, MBT timing criteria available are 50%MFB and PCPL, and the composite MBT timing criterion calculation utilizes both of them as follows

\[
C_{\text{MBT}} = [\alpha_{\text{50%MFB}} \cdot (50\%\text{MFB} - 50\%\text{MFB}_{\text{OFFSET}}) \\
+ \alpha_{\text{50%MFB}} \cdot (PCPL - PCPL_{\text{OFFSET}})] / \gamma \quad \text{(Eq. 4)}
\]

where, \( \gamma = \alpha_{\text{50%MFB}} + \alpha_{\text{50%MFB}} \neq 0 \).

**CONTROL STRATEGY AND TEST CONFIGURATION**

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 [12]. The closed-loop control architecture of MBT timing is limited by knock constraints. Instead of controlling engine spark timing using calibrated tables as a function of engine speed, load, etc., the engine spark timing control is generated by a closed-loop PI (Proportional and Integral) controller using information derived from in-cylinder ionization sensing as the feedback signal.

Inputs to the closed-loop MBT timing controller (see Figure 3) are the individual in-cylinder ionization signals and the current engine operational information such as the engine speed, load, etc.

**In-cylinder Ionization vector:**

The individual cylinder ionization signal is sampled at a one crank degree resolution for all cylinders. Each 120 crank degree of ionization signal is sampled right after the completion of dwell event for each individual cylinder. The sampled in-cylinder ionization signal is made available for composite MBT timing criterion estimation and closed-loop control after engine expansion stroke for each corresponding cylinder.

**Knock intensity:**

Knock intensity is produced using an analog circuit that filters the corresponding ionization signal over a given knock window using a bandpass filter, amplifying the resulting signal, and integrating its absolute magnitude.

**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 3).

The MBT timing estimation block in Figure 3 calculates the composite MBT timing criterion for the current cylinder using the proposed algorithm in the previous section. Parameters \( \alpha_{\text{MAMFB}} \), \( \alpha_{\text{50%MFB}} \), and \( \alpha_{\text{50%MFB}} \) are set to one and one, as appropriate, and the offsets PCPL_{OFFSET} and 50%\textit{MFBOFFSET} are set to 15° and 9°, respectively.

The MBT estimation block also calculates the misfire index using the in-cylinder ionization signal. Misfire of the corresponding cylinder is declared if the integration of the ionization signal over a specific window right after ignition event 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 controller. The error between MBT reference and the composite MBT timing criterion is used as an
input to the PI controller. The MBT reference signal is set to zero for this test.

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.

The closed-loop MBT timing controller was validated in an engine dynamometer using a two-liter four-cylinder engine. The engine was controlled by the engine dynamometer except for engine spark timing. All engine sensors were connected to the dynamometer controller. The engine dynamometer 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 prototyping both open loop and closed-loop spark timing control. Kistler pressure sensors were installed in every cylinder for comparing with in-cylinder ionization signals.

The dSpace PX-10 expansion box, used for closed loop MBT timing control, consists of a main processor card, a fast A/D (Analog to Digital) 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, synchronized by the camshaft sensor, also calculates current crank angle to arrange the sampled ionization signal into an array during compression and expansion cycle of the corresponding cylinder. The crank angle also generates software interrupt to enable the combustion event-based closed-loop spark control calculation. 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 and is triggered by the crankshaft encoder. The second runs every 180 crank degrees (for a four cylinder engine) and is triggered by the first crank based process through a 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. 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 3, runs every 180 crank degrees.

### TEST RESULTS AND ANALYSIS

Before the results of closed-loop MBT timing control are discussed, the results of estimating the composite MBT timing criterion are presented. The composite MBT timing criterion is called MAMFBI. Figure 4 shows the estimated MBT timing criterion MAMFBI. The engine was running at 1500 RPM with 7.0 bar BMEP load, and the ignition timing is -21° ATDC. The data shown in Figure 4 is 100 cycles of data for cylinder three only. It can be observed that the engine is running close to MBT timing since the average of the estimated MAMFBI is closed to zero. The ionization MBT timing detection algorithm is validated over the engine operational map using offline test data.

![Figure 4 MBT criterion from ionization signal](image1)

![Figure 5 MBT timing criteria vs. timing sweep](image2)
Figure 5 shows the relationship between estimated ionization MBT criterion MAMFBI and in-cylinder pressure MBT criteria MAMFBP, 50%MFB, and PCP locations. The data shown in Figure 5 is a result of spark-timing sweep when the engine was operated at 1500 RPM with 7.0 bar BMEP load. The spark timing varies from 13° BTDC to 25° BTDC. The top graph of Figure 5 shows the MBT timing criteria for cylinder number three, and the bottom one shows the average MBT timing criteria over all four cylinders. It is clear that the ionization MBT timing criterion MAMFBI is very close to the MAMFB criterion calculated using in-cylinder pressure [12] (called MAMFBP in the graph). From the average MBT timing criteria plot, it can be concluded that the engine MBT timing is around 21° BTDC since both MAMFBI and MAMFBP are close to zero. An important observation of both top and bottom graphs is that all four MBT timing criteria are almost linear against the spark timing sweep, that provides a good closed loop control characteristics. Test data for the other cylinders is similar to cylinder three.

Figure 6 shows the response of three MBT timing criteria under closed loop MBT timing control. The three MBT timing criteria are PCP location, 50%MFB location, and MAMFBI. The engine is operated at 1500 RPM with 7.0 Bar BMEP load. It is clear that all three MBT timing criteria remain at their MBT locations, respectively. That is, the PCP location is around 14° to 16° BTDC, 50%MFB location is around 8° to 10° BTDC, and MAMFBI is closed to 0° BTDC.

Another aspect of analyzing closed-loop control of engine MBT timing is from a stochastic perspective. It is well known that for a linear dynamic system with a stationary stochastic process input, closed-loop controllers, such as an LQG (Linear Quadratic Gaussian) controller, are able to reduce closed-loop system output variances. Figure 7 shows output variances of MBT timing criteria (PCP and 50%MFB locations) for both open loop and closed-loop control. The engine operating condition is the same as the open-loop control case shown in Figure 4. It is clear that closed-loop control using ionization based MBT timing feedback reduces cycle-to-cycle variances shown in Figure 7.

Figure 8 shows the results of closed-loop ionization MBT timing control during engine warm up process. The engine was operating at 1500 RPM with 64 NM (Newton-Meter) load. The whole process lasted for about 10 minutes and resulted in almost ten thousand engine cycles. The starting engine coolant temperature is about 34° C and the ending temperature is about 93° C. The top graph of Figure 8 shows the relationship between engine coolant temperature and engine MBT
timing. In order to keep the composite ionization MBT timing criterion at or around TDC location, the ignition timing has to be advanced to compensate relatively slow combustion when engine is cold. It is clear that during the ten-minute warm-up process, the closed-loop MBT timing controller moves the spark timing in a retard direction from around 28° BTDC to 21° BTDC. During this warm up process, the burn-rate increases and the corresponding MBT spark timing moves back in a retard direction.

The second graph of Figure 8 from top shows the average PCP location of four cylinders and the bottom four graphs show the 50%MFB locations for all four cylinders. It can be observed that the mean PCP location is between 15° and 16° ATDC during the engine warm-up process, and that all 50%MFB location for all for cylinder is between 8° and 10° ATDC. This validates that engine operates at its MBT timing during the engine warm up process, and it also shows that closed-loop MBT timing control using ionization feedback is able to operate the engine at its MBT timing during the temperature transition.

CONCLUSION

A new composite MBT timing criterion, using in-cylinder ionization signal, is developed based upon the correlation between in-cylinder ionization and pressure signals. The concept has been validated over engine operational range. The potential benefit of using this new ionization based MBT criterion for closed-loop control is reduced calibration and a reduced cycle-to-cycle variation with a relative low cost compared to using in-cylinder pressure signals. Closed-loop MBT timing control was evaluated using the composite ionization MBT timing criterion.

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REFERENCES


CONTACT

Guoming (George) Zhu, Ph.D., Visteon Corporation, 17000 Rotunda Dr, Dearborn, MI 48120, USA. E-mail: gzhu1@visteon.com (313-755-9185)

DEFINITIONS, ACRONYMS, ABBREVIATIONS

MBT: Maximum Brake Torque
PI: Proportional and Integral
ATDC: After Top Dead Center
PR: Pressure Ratio
<table>
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>PCP</td>
<td>Peak Cylinder Pressure</td>
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<tr>
<td>MFB</td>
<td>Mass Fraction Burned</td>
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<tr>
<td>DATDC</td>
<td>Degrees After Top Dead Center</td>
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<td>EGR</td>
<td>Exhaust Gas Recirculation</td>
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<tr>
<td>TDC</td>
<td>Top Dead Center</td>
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<tr>
<td>MAMFB</td>
<td>Maximum Acceleration of Mass Fraction Burned</td>
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<tr>
<td>50%MFB</td>
<td>50% Mass Fraction Burned</td>
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<tr>
<td>PCPL</td>
<td>Peak Cylinder Pressure Location</td>
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<td>Air to Fuel</td>
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<tr>
<td>BMEP</td>
<td>Brake specific Mean Effective Pressure</td>
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<td>PRM</td>
<td>Pressure Ratio Management</td>
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<tr>
<td>MAMFBI</td>
<td>Maximum Acceleration of Mass Fraction based upon Ionization</td>
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<tr>
<td>MAMFBP</td>
<td>Maximum Acceleration of Mass Fraction based upon Pressure</td>
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<td>CL</td>
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<td>LQG</td>
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