Improvements in Knock Control

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Abstract—The aim of this work is to develop an improved method for knock control in gasoline engines. This should enable higher power output compared to existing methods of knock control without raising the level of knock probability. An analysis of a known knock controller shows, that information about distance to knock limit is not used in knock control. Based on this analysis a design of a new knock controller is developed. This controller uses cylinder-pressure signals to estimate the distance to knock limit and to control ignition angle. An improvement in power output is proven using engine tests.

I. INTRODUCTION

Engine knock is an irregular combustion phenomenon, which can occur in spark ignited gasoline engines. After spark ignition has started the regular combustion, a flame front propagates through the combustion chamber. Heat release during combustion stroke causes pressure and temperature inside the cylinder to increase. High cylinder pressure compresses the unburned gas fraction too. If temperature and pressure in the unburned gas zone reach a critical level, chemical kinetic mechanisms can cause autoignition, even before the gas is burned by the regular flame front.

Knocking combustion is known to damage the engine. In [1], [2], [3] and [4] examples for engine failures caused by knock are given. To avoid knocking combustion, usually ignition timing is retarded. This means to decrease not only knock probability but power output of the engine too. Hence an acceptable trade-off between high power-output and safe engine operation has to be found. To achieve this, modern production car engines are equipped with a knock sensor (acceleration sensors or in-cylinder ion-current sensors) and a knock controller. Since the knock sensor provides information only under knocking conditions, it is assumed that the trade-off situation can be improved, if additional information about the combustion cycle is applied.

Section II of this paper gives a short introduction into knock detection and knock control. A method to estimate a distance to the knock limit is developed in section III. A new algorithm to control knock based on this distance is shown in section IV. In section V the performance of basic knock controllers and distance-based knock controllers is compared.

II. CONVENTIONAL APPROACH TO KNOCK CONTROL

Often measured knock signals are evaluated in time domain [5], [6]. Usage of time windows allows selection of single combustion events. Bandpass filters suppress noise. The windowed and filtered knock signal \( x \) is used to calculate a knock intensity value \( y_{ki} \), e.g.

\[
y_{ki} = \max_n (|x(n)|)
\]  

(1)

If knock intensity exceeds a threshold value \( y_0 \), the combustion cycle is regarded as knocking. The knock controller uses knock intensity as an input signal to control ignition timing so that a certain knock rate is not exceeded.

Figure 2 shows the structure of a basic knock controller [4]. Ignition angle \( \alpha_{ign} \) is the sum of knock controller output \( \alpha_{kc} \) and base ignition angle \( \alpha_b \). If a knocking
combustion occurs, controller retards $\alpha_{kc}$ for the next combustion cycle ($q + 1$). Retardation step size is set by $K_n$. If no knock occurs ignition angle is advanced in small steps $K_p$. Control law can be expressed as:

$$
\alpha_{kc} (q) =
\begin{cases}
\alpha_{kc} (q - 1) - K_n , & \text{if } y_{ki} (q - 1) \geq y_0 \\
\alpha_{kc} (q - 1) + K_p , & \text{if } y_{ki} (q - 1) < y_0
\end{cases}
$$

(2)

The actuator signal $\alpha_{kc}$ shows typical saw-tooth oscillations. These oscillations are caused by the nonlinear control algorithm and can be considered as auto-oscillations.

III. DISTANCE TO KNOCK LIMIT

Basic knock controllers as shown in section II use knock intensity to control ignition angle. There is no information about the current distance to knock limit available. This is why knock controllers usually retard ignition angle a large step after knocking combustion cycles but only slowly advance ignition angle if no knock occurs. These periods of retardation cut down the torque output of the engine. Knock control algorithm could be improved if an error signal showing the distance to the knock limit was available.

Evaluation of resonant knock oscillations is not suitable to calculate such a distance value. While the engine is operated in non-knocking mode, knock intensity signal generally shows values close to zero. Even if the ignition angle (and the distance to knock limit) is changed there is almost no change in knock intensity (figure 3). To calculate the distance to knock limit it is necessary to take causes for knock into account.

This section shows how to determine a knock limit and to calculate the distance between any combustion cycle and this limit. This information will be fed into an new improved knock controller. The low-pass filtered cylinder pressure signal is used to calculate its maximum value $p_{max}$. The high-pass filtered cylinder pressure signal is used to calculate knock intensity $p_{ki}$.

Figure 3 shows relations between ignition angle $\alpha_{ign}$ and knock intensity $p_{ki}$. Since knock intensity values are usually assumed to be lognormal distributed [7], measurement data in 3 are shown on a logarithmic scale too. Advancing the ignition causes knock. By retarding the ignition knocking combustion can be prevented completely. Within the non-knocking range knock intensity can not provide any information about the distance to the knock limit. For the estimation of such a distance value, other measurement categories should be considered.

In figure 4 the correlation between knock intensity values $p_{ki}$ and cylinder pressure maximum values $p_{max}$ is shown. There is a correlation between both signals. Knocking combustion can occur if cylinder pressure maximum exceeds a certain limit. Larger cylinder pressure maximum go together with higher knock intensities. If there is a limit to knock intensity $p_{ki}$, it is also possible to determine a knock limit to the cylinder pressure maximum $p_{max}$.

Figure 5 shows values of cylinder pressure maximum $p_{max}$ and ignition angle $\alpha_{ign}$. The strong correlation between both signals is obvious. It is possible to fit a regression line to the data. Using the equation

$$
e_\alpha = \frac{d\alpha}{dp_{max}} \cdot e_p, \quad (3)$$

a pressure maximum difference $e_p$ can be converted into an ignition angle difference $e_\alpha$.

So far it has been demonstrated that it is possible to calculate the distance to knock limit by evaluation of measured cylinder pressure values. Measurement data of $\alpha_{ign}$, $p_{max}$ and $p_{ki}$ are used to calculate Pearson’s linear correlation coefficient and Spearman’s rank correlation coefficient [8]. Results are presented in table

<table>
<thead>
<tr>
<th>Signal 1</th>
<th>Signal 2</th>
<th>$r_{pearson}$</th>
<th>$r_{spearman}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_{ign}$</td>
<td>$P_{max}$</td>
<td>0.94</td>
<td>0.95</td>
</tr>
<tr>
<td>$\alpha_{ign}$</td>
<td>$p_{ki}$</td>
<td>0.63</td>
<td>0.82</td>
</tr>
<tr>
<td>$p_{max}$</td>
<td>$p_{ki}$</td>
<td>0.73</td>
<td>0.84</td>
</tr>
</tbody>
</table>

TABLE I
CORRELATION COEFFICIENTS CALCULATED FROM $\alpha_{ign}$, $P_{max}$ AND $P_{ki}$
I. They show advantages of the evaluation of cylinder pressure maximum over evaluation of knock intensity and ignition angle. Compared to cylinder pressure maximum the ignition angle effects knock less directly. Cylinder pressure maximum is closely correlated to the temperature in the unburned gas zone, which is a major cause for the occurrence of knock. It can be concluded that it is more evident to determine a knock limit in cylinder pressure maximum \( p_{\text{max}} \) than in ignition angle \( \alpha_{\text{ign}} \).

IV. NEW APPROACH TO KNOCK CONTROL

The previous section showed, how to determine a knock limit and the distance to this limit using cylinder pressure measurements. Figure 6 shows a general concept for a new knock control algorithm. Basic knock control algorithms use only knock intensity to adjust ignition angle. This neglects any parameter causing knock. Figure 6 shows several parameters (engine design, operational parameters, actuators) which directly influence combustion as well as pressure and temperature in the unburned gas zone. Using a distance value, knock control can adjust ignition timing very close to the knock limit. There is no need to retard ignition angle after a single knock event. This provides a higher average torque output while knock probability is not raised.

Such a distance-based knock controller has been presented by the authors in [9] and [10]. Figure 7 shows a rough structure of this new knock controller. Cylinder pressure signal \( p \) is used on two different paths. A high-pass filtered signal \( p_{\text{hp}} \) is used to detect knocking combustions. The low-pass filtered cylinder pressure \( p_{\text{lp}} \) does not contain any resonant oscillations, but can be used to calculate certain values, e.g.:

- values that describe the shape of cylinder pressure curve (cylinder pressure maximum, maximum of derivative of cylinder pressure)
- values of heat release signal (start of heat release, end of heat release)
- chemical kinetic values [11]

Knock detection enables to find a knock limit for the calculated low-pass cylinder pressure property. Distance between properties of the current cycle and the knock limit is fed into the knock controller which calculates the actuator signal \( \alpha_{\text{kC}} \).

Figure 8 shows the controller structure in more detail. Cylinder pressure maximum \( p_{\text{max}} \) and knock intensity \( p_{\text{ki}} \) are used as inputs. The smoothed cylinder pressure values \( \bar{p}_{\text{max}} \) are compared to the setpoint \( p_{\text{max}}^{\text{set}} \). The resulting distance to the knock limit \( e_{\text{p}} \) is converted into an equivalent ignition angle difference \( e_{\alpha} \). The actuator signal of the controller is \( \alpha_{\text{kC}} \).

V. ENGINE TESTS AND RESULTS

An engine test bed was used to compare the performance of a basic knock control algorithm to a new distance-based controller. The values used as input signals (knock intensity \( p_{\text{ki}} \) and cylinder pressure maximum \( p_{\text{max}} \)) were extracted from the measured cylinder pressure signals of a four cylinder gasoline engine.

<table>
<thead>
<tr>
<th>index</th>
<th>controller</th>
<th>parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>distance-based</td>
<td>( L = 1,3 )</td>
</tr>
<tr>
<td>2</td>
<td>distance-based</td>
<td>( L = 1,7 )</td>
</tr>
<tr>
<td>4</td>
<td>basic</td>
<td>( K_n = 3,00^\circ, K_p = 0, 75^\circ/30 )</td>
</tr>
<tr>
<td>5</td>
<td>basic</td>
<td>( K_n = 2,25^\circ, K_p = 0, 75^\circ/30 )</td>
</tr>
<tr>
<td>6</td>
<td>basic</td>
<td>( K_n = 1,50^\circ, K_p = 0, 75^\circ/30 )</td>
</tr>
</tbody>
</table>

TABLE II

TESTED KNOCK CONTROLLERS

Table II lists the tested controllers. Every controller has its index which will be referred throughout this section.

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Fig. 5. Relationship between ignition angle and cylinder pressure maximum

Fig. 6. Concept of a distance-based knock controller
Figure 7. Structure of a distance-based knock controller

Figure 8. Distance-based knock controller

Figure 9 shows examples of knock intensity and actuator signals while using a basic knock controller (index 5). The actuator signal $\alpha_{kr}$ shows large retardation steps after every single knocking combustion.

Figure 10 shows values of the indicated mean pressure during compression and combustion stroke $p_{miH}$ referring to figure 9. These values can be regarded as a measure for the torque generated by the combustion during a single cycle (pumping losses are not considered). $p_{miH}$ and $\alpha_{kr}$ are correlated. Therefore, it can be concluded, that ignition retardation by knock control significantly reduces torque output.

Figure 11 shows input signal $p_{max}$ and actuator signal $\alpha_{kc}$ of a distance based knock controller. There are no large retardation steps after knocking combustion cycles.

Figure 12 shows indicated mean pressure during compression and combustion stroke $p_{miH}$ and knock intensity values $p_{ki}$ referring to figure 11. There are only few knocking combustions. Because distance-based knock control adjusts ignition angle without large steps, the indicated mean pressure does not show large variations.

To evaluate the performance of different knock controllers generated torque and resulting knock intensities must be compared. Table III shows averaged values of indicated mean pressure during compression and combustion stroke and knock probability. Figure 13 displays these data graphically. Results show an increased torque output of the engine if a distance based knock controller is used. In this case the achieved improvement amounts 0, 15...0, 3%. Because the increased torque is achieved without addi-

Fig. 9. Knock intensity and ignition angle for the basic knock controller

Fig. 10. Indicated mean pressure for the basic knock controller

Fig. 11. Cylinder pressure maximum and ignition angle for the distance-based knock controller

Fig. 12. Knock intensity and indicated mean pressure for the distance-based knock controller
<table>
<thead>
<tr>
<th>index</th>
<th>$P_{\text{mit}}$ [bar]</th>
<th>$\sigma_{\text{av}}$ [°btdc]</th>
<th>probability of knock [%]</th>
<th>$P_{\text{ki}}$ [bar]</th>
<th>number of cycles</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.37</td>
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<td>16.23</td>
<td>1.34</td>
<td>0.34</td>
<td>20068</td>
</tr>
</tbody>
</table>

TABLE III
RESULTS OF CONTROLLER TESTS

![Fig. 13. Improvement of indicated mean pressure](image)

tional fuel consumption this means the efficiency of the engine is improved too.

VI. CONCLUSIONS

Goal of the presented work was to develop an improved knock controller.

This should increase torque output of the engine without increasing knock intensity or fuel consumption.

Basic knock controllers react to knocking combustion by retarding ignition angle. The absence of a distance or error signal can be seen as a major disadvantage of these algorithms. This is why a way to calculate such a distance signal by analyzing cylinder pressure signals was developed. A new distance-based knock controller uses this signal to control ignition angle without large retardation steps. This enables to adjust a more advanced average ignition angle and to generate a higher torque output of the engine.

REFERENCES