

Engine Start-Up Optimization using the Transient Burn Rate Analysis

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ABSTRACT

The introduction of CO₂-reduction technologies like Start-Stop or the Hybrid-Powertrain and the future emission legislation require a detailed optimization of the engine start-up. The combustion concept development as well as the calibration of the ECU makes an explicit thermodynamic analysis of the combustion process during the start-up necessary.

Initially, the well-known thermodynamic analysis of in-cylinder pressure at stationary condition was transmitted to the highly non-stationary engine start-up. There, the current models for calculation of the transient wall heat fluxes were found to be misleading [1]. Therefore, adaptations to the start-up conditions of the known models by Woschni [2], Hohenberg [3] and Bargende [4] were introduced in [5] for calculation of the wall heat transfer coefficient in SI engines with gasoline direct injection.

This paper shows how the indicated values can be measured during the engine start-up. Furthermore, the methods of deriving the piston positions and the engine speed from the time-based data are described. With these, the transient burn rate analysis is performed using the introduced approaches for the wall heat transfer calculation.

For the validation of the thermodynamic analysis start-up behavior of 3-, 4- and 6-cylinder SI engines are investigated and the results are discussed. In addition to this, a 3 cylinder CI engine start-up is analyzed to verify the novel wall heat transfer approach for Diesel engines.

Optimization of a 6-cylinder engine start-up is shown using the transient burn rate analysis results which demonstrate the efficiency potential for the application process.

INTRODUCTION

An in-depth look at vehicle emissions shows that the exhaust gas emitted during cold start and in the subsequent warm-up period plays a decisive role. For this reason, measures to improve start-up performance have a direct effect on the overall result across the driving cycle. A detailed analysis of the processes in the combustion chamber during start-up is advantageous in understanding the development of the combustion process and also for the data calibration of the engine management system. For this, a cycle-by-cycle transient thermodynamic analysis of the engine start-up is needed. In [1] the basic description of such an analysis was given. There, the thermodynamic analysis of engine start-up's using the wall heat transfer models by Woschni [2], Hohenberg [3] and Bargende [4] was performed leading to undesirable results. Hence, for a more accurate thermodynamic analysis and for an efficient application of the engine start-up, new measurements of the transient wall heat flux and a new approach describing the transient heat transfer during the engine start-up were necessary. As a result of this work, adaptations of the models by Woschni, Hohenberg and Bargende to the start-up conditions were introduced in [5] for SI engines with gasoline direct injection. Because of its simplicity and accuracy stationary thermodynamic analysis of combustion engines is often performed using the Woschni model. Therefore, the first validation of the introduced adaptations presented in this work is done by using the Woschni model extension. Therein, the heat flux to the combustion chamber walls is given by

$$\frac{dQ_w}{dt} = \alpha_{start} \cdot A_w \cdot (T_w - T) \quad (1)$$

where the wall heat transfer coefficient α_{start} is calculated using

$$\alpha_{start} = 130 \cdot d^{-0.2} \cdot p^{0.8} \cdot T^{-0.53} \cdot w_{start}^{0.8} \quad (2)$$

The wall heat transfer relevant gas velocity w_{start} is described for start-up conditions ($150 \text{ min}^{-1} < n_{engine} < 1000 \text{ min}^{-1}$) by

$$w_{start} = \left(2.14 - 0.795 \cdot c_{m,c} + \frac{293.15}{T_w} \right) \cdot C_1 \cdot c_m^* + \dots$$

$$\frac{1}{4} \cdot \left(\frac{V_c}{V} \right)^{\frac{1}{3}} \cdot C_2 \cdot \frac{V_h \cdot T_1}{p_1 \cdot V_1} \cdot (p - p_0) \quad (3)$$

$$C_1 = 2.28 \quad C_2 = 3.24 \cdot 10^{-3}$$

Herein, c_m^* presents the “mean” piston speed calculated by means of the transient engine speed $n(t)$

$$c_m^* = \frac{h \cdot n(t)}{30} \quad (4)$$

and $c_{m,c}$ is used for describing the speed level during the compression stroke, determined by the mean compression speed n_{comp}

$$c_{m,c} = \frac{h \cdot n_{comp}}{30} \quad (5)$$

As discussed in [5], the presented Woschni model adaptation gives very good results by analyzing the start-ups on the single cylinder engine used for the wall heat flux measurements. For further validation of the model, additional start-up time based measurements on various engines and conditions are needed.

MEASURING ENVIRONMENT FOR ENGINE START-UP INVESTIGATION

To perform the transient thermodynamic analysis of the start-up combustion [1], time based data acquisition on the test bed is needed. The standard crank based indication is not sufficient, because of the different time delay per crank angle resolution due to the high crank shaft acceleration during the engine run-up. Crank angle based start-up measurements lead to uncomparable thermodynamic results of the start-up analysis, which reduce the application work efficiency. For the time based indication of the relevant data, a time recorder is needed. Because of the usually existing implementation in the test bed environment, a data acquisition system which

allows for time and crank angle based measurement is recommend. In Fig. 1, a schematic overview of the start-up measuring environment is shown. During the start-up, the data acquisition computer stores the values provided by the amplifier. After the test, the thermodynamic analysis can be performed and the results used for optimizing the start-up behavior, e.g. to set revised injection/ignition timing of the ECU.

For the transient thermodynamic analysis, the following time base indicated values are needed:

- Crank Degree Mark - CDM signal
- Trigger signal of specified cylinder TDC (in order cylinder 1)
- In-cylinder pressure traces of all cylinders

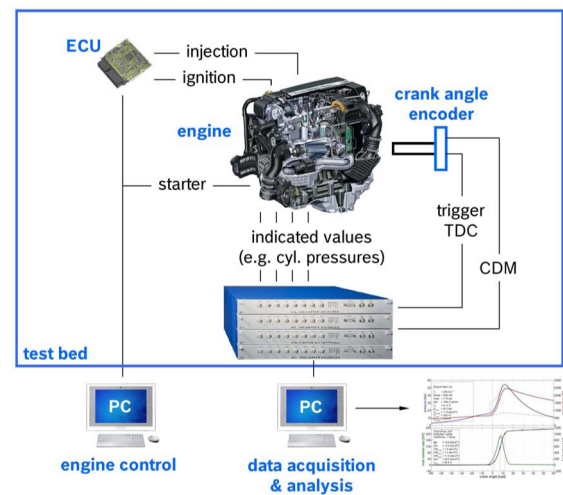


Figure 1. Scheme of the transient start-up measurement on the test bed

Optional values also useful for the start-up analysis and optimization are:

- Intake port pressure traces of all cylinders
- Injection and ignition signals of all cylinders
- Fast FID measurement of the HC-emissions

In addition to this, some important global conditions should be noted:

- Ambient pressure and temperature
- Engine temperature (water, oil)
- Fuel quality
- Hardware and software (ECU) settings

Additionally, an appropriate sampling rate for the time based measurement should be found. Too high frequencies lead to

very big data files with high handling times. If the sampling rate is too low, the analysis can not be performed properly. The minimum sampling rate for the measurement can be obtained by the Nyquist-Shannon theorem Eq. (6), which defines the lowest sampling frequency f_{sample} to be equal to the double of the monitored rate f_{appear} .

$$\frac{f_{sample}}{f_{appear}} \geq 2 \quad (6)$$

In case of the transient start-up measurement on the test bed, the signal of the crank degree marks is the value which appears with the highest frequency. Depending on the used crank angle encoder maximum resolution Δca , the sampling rate is given by

$$f_{sample} \geq 2 \cdot f_{appear} = 2 \cdot n \cdot \frac{360}{\Delta ca} \quad (7)$$

For a crank angle encoder resolution of $\Delta ca = 0.5$ cad and maximum engine speed $n = 2000 \text{ min}^{-1}$ (start-up) $f_{sample,min}$ results in

$$f_{sample,min} = 2 \cdot \frac{2000 \cdot 360}{60s \cdot 0.5} = 48 \text{ kHz} \quad (8)$$

In this case, $f_{sample,min}$ is the lowest sampling rate to perform the analysis correctly. The most available data acquisition systems allows for higher rates. In this work, the sampling rate of the time based measurement was set to $f_{sample} = 200 \text{ kHz}$ because of the higher crank angle encoder resolution available on some investigated engines.

The start-up measurement should begin before the first turn of the starter and ends after a defined engine speed is reached. At the application process, a recommend sampling time is $t_{sample} = 4 \text{ s}$ for analyzing also long start-up periods due to misfires or incomplete combustions.

ENGINE START-UP ANALYSIS

After the measurement is stored, some pre-processing of the raw data is needed to perform the transient thermodynamic analysis. In the following, all the necessary steps are described.

CRANK ANGLE DETERMINATION

First, the position of the engine, i.e. the time resolved crank shaft angle, is determined. For this, the time based CDM-signal of the crank angle encoder is used. Usually, the

encoder delivers per crank angle resolution, e.g. $\Delta ca = 0.5$ cad, a trailing edge event. The top of Fig. 2 shows the time based CDM signal during engine cranking and the Δca in between two trailing edges.

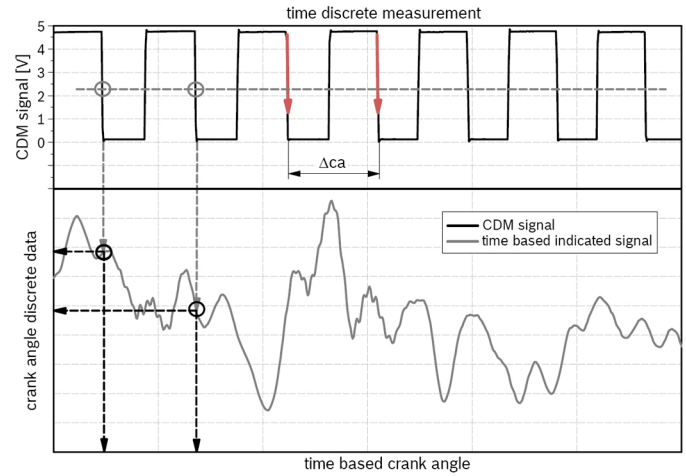


Figure 2. Determination of the crank angle discrete data from the time based measurement using the CDM information

For the determination of these events, one half of the CDM-signal level is used as a threshold value. For each of these discrete points in time measured data is assigned. With this, the time discrete measurement becomes a crank angle discrete data set. Fig. 2 makes the data assignment method clear. Also seen in Fig. 2 is the fact of data loss during this operation, because all the time measured data within one Δca get lost. For the thermodynamic analysis it is essential to calculate each measured in-cylinder pressure value in accordance with the combustion chamber volume. This can only be done if the piston position, i.e. crank angle, is assigned correctly. Hence, the crank angle encoder resolution defines the resolution of the later analysis. Having the Δca vs. time correlation, the calculation of the engine speed trace is easily possible by

$$n = \frac{1}{6} \cdot \frac{d\phi}{dt} \quad (9)$$

The discrete crank angle values can now be integrated to a continuous crank angle vector related to the time scale of the measurement. The next step is to obtain the absolute piston position on the determined crank angle scale. For this, the trigger signal of the crank angle encoder is used. The trigger signal consists of one trailing edge per crank shaft revolution, see Fig. 3 top. At the beginning of the measurements, the offset ΔTDC between the trigger signal and the physical TDC position of a specified cylinder, e.g. cylinder 1, should be determined. This can be done by using an in-cylinder mounted capacitive probe during a motored engine run.

Measurements on a single cylinder research engine in [1] have shown that if the inertia of the crank train is high enough, adjustments of the TDC-offset can appear during the high engine acceleration at start-up. They are caused by torsion and elongation of the crank train, which change the offset between the crank shaft mounted encoder and the specified piston TDC position. In this case, the speed dependent offset must be considered during the thermodynamic analysis. For engines studied in this work, a transient speed-up test was performed to determine the ΔTDC behavior during the engine run-up, see Fig. 4. For the investigated 3 and 4 cylinder engines, the ΔTDC adjustment at start-up relevant engine speeds was found to be negligible.

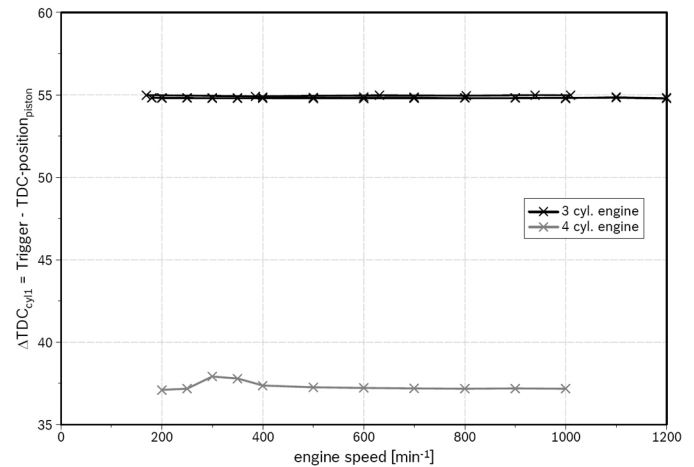


Figure 4. Results of ΔTDC measurement during transient engine acceleration test for several engines.

WORK CYCLE ORDERING

For the cycle-by-cycle performed transient burn rate analysis, the crank angle based data are separated into single cycles and ordered by means of the engine firing order. The firing order is usually known and can be stored within the measurement or easily determined evaluating the time information of the in-cylinder pressure peaks. Fig. 6 shows as an example the work cycle assembly of a 6-cylinder engine start-up. Because of the cylinder volume available, a fast calculation of the reached effective indicated work (*imep*) during the separate cycles is possible. The *imep* level can be used for the determination of the first firing cycle during the measurement and for exclusion of the motored phase of the start-up, if not relevant for the investigation.

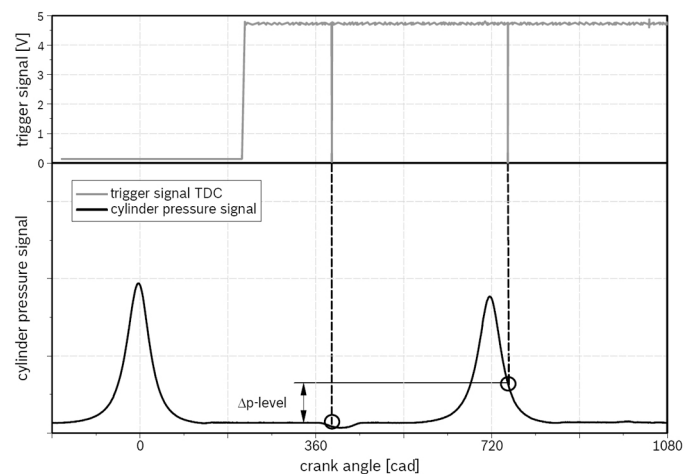


Figure 5. Finding the absolute engine position using the TDC trigger signal and the in-cylinder pressure.

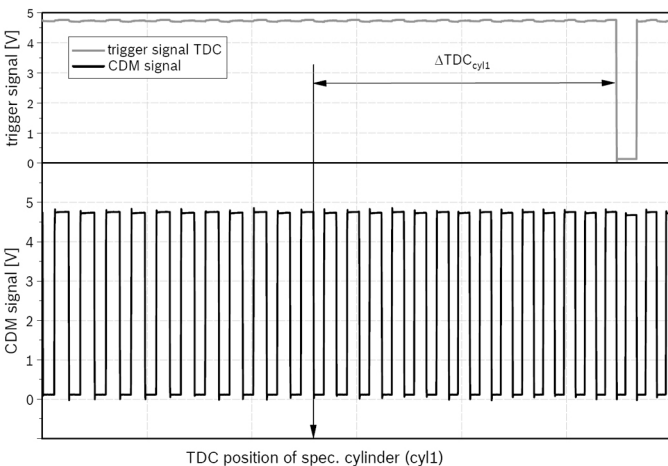


Figure 3. Trigger and CDM signal of the crank angle encoder. ΔTDC describes the crank angle offset to a specified cylinder TDC.

With ΔTDC the continuous crank angle vector can be shifted to the TDC position of the specified cylinder. The last step to determine the absolute engine position is to find out whether the found TDC trigger corresponding to an ignition or gas exchange top dead center. This can be easily done by a relative comparison of the measured in-cylinder pressures at the following TDC trigger events as shown in Fig. 5.

Thereby, the higher pressure level indicates an ignition TDC of the specified cylinder. With this information, the absolute crank angle base is found for the entire start-up measurement.