A New Data Acquisition and Processing System for In-Vehicle Combustion Analysis

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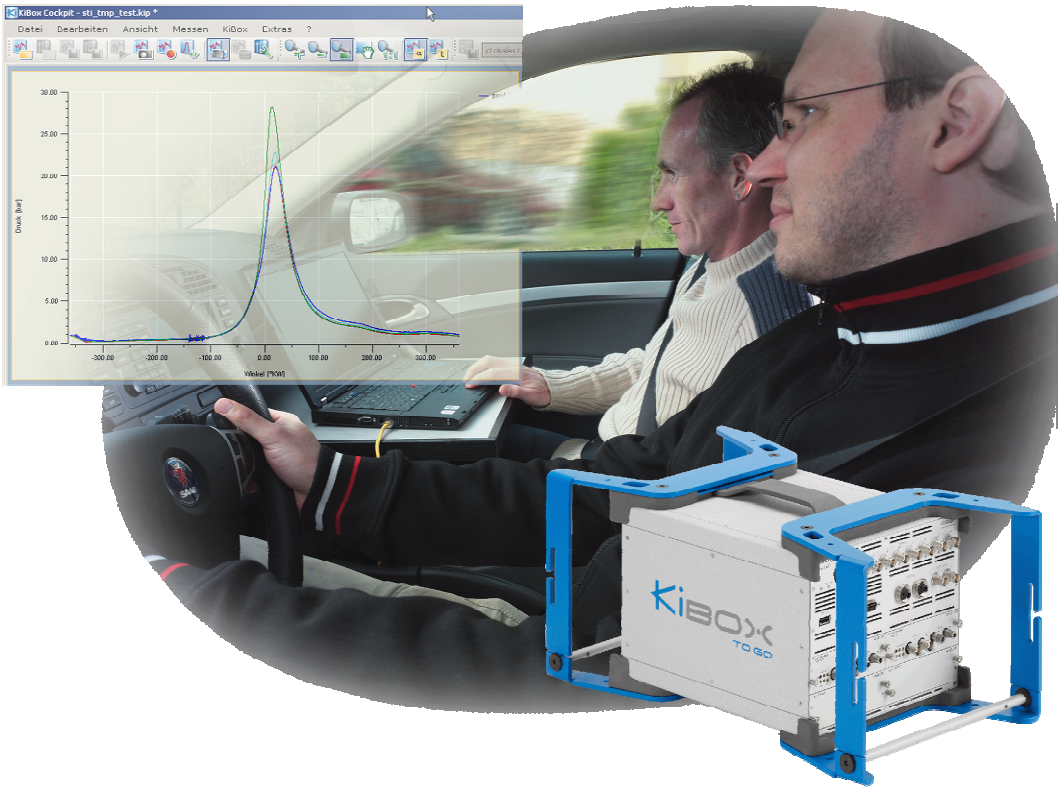

With KiBox, Kistler Instrumente AG has developed a new data acquisition and processing system specially designed for in-vehicle combustion analysis. Apart from its innovative data acquisition concept and easy integration into the INCA calibration system, KiBox comes with a number of new features representing the leading edge of technology and beyond. This enables combustion analysis values to be displayed in real-time and to be analyzed simultaneously with other control variables of the engine management system.

1. Introduction

The measurement and thermodynamic analysis of in-cylinder pressure (referred to in this article as "combustion analysis") continues to be the essential tool for determining the quality of energy conversion in internal combustion engines. The evaluation of combustion pressure and the related change in combustion chamber volume provides data which permit a characterization of the combustion and a quantification of the thermodynamic process. Combustion pressure can be measured directly with piezoelectric pressure sensors. The volume change in the combustion chamber can be measured only indirectly from the acquisition of the crank angle position, the crank drive kinematics and the geometrical data of the cylinder.

Today, combustion analysis is typically carried out on engine test stands for both steady state and transient engine speed and load points. In addition, combustion analysis is extremely useful in on-road testing for validating the calibration of the engine management system and for trouble-shooting purposes. Only combustion analysis makes it possible to observe and quantify precisely the effects that the highly complex control processes of the complete engine system have on the actual combustion under all real operating conditions. Thus, combustion analysis helps to improve our mastery of complex modern engine control units (ECU), to carry on system optimization under everyday driving conditions and to shorten the overall development process. In-vehicle combustion analysis is also becoming even more important in view of the greatly increased engine performance levels of down-sizing concepts.

2. Basic Layout of Combustion Analysis Systems

A conventional combustion analysis system consists of a pressure sensor, connecting cable, amplifier and crank angle encoder, together with data acquisition and evaluation.

Pressure sensor: In view of the wide pressure range, the high operating temperatures in the combustion chamber and the ultra-fast combustion processes, piezoelectric pressure sensors are needed to achieve precise pressure measurements. These sensors yield a charge proportional to the pressure. Apart from the physical characteristics of the sensor itself, one of the main factors affecting the achievable precision of measurement is the way in which it is installed in the engine.

Connecting cable: The connecting cable serves to transmit the electrical charge from the sensor to the amplifier. As the sensor charge yields are extremely small in absolute terms, the cable and the connector must provide a very high degree of electrical insulation. In addition, the cable needs to be triboelectrically optimized in order to minimize parasitic charge shifts caused by friction on the inner insulation arising from cable movements.

Charge amplifier: The electrical charge of the pressure sensor is converted, with great precision, into a proportional voltage signal through integration in the amplifier.

Crank angle encoder: The crank shaft angle serves as the basis for the acquisition of the related data and the calculation of the combustion analysis values. For each revolution, the

optical incremental encoders that are typically used provide a fixed number (e.g. 360) of crank degree marks (CDM) and a synchronization mark (TRG).

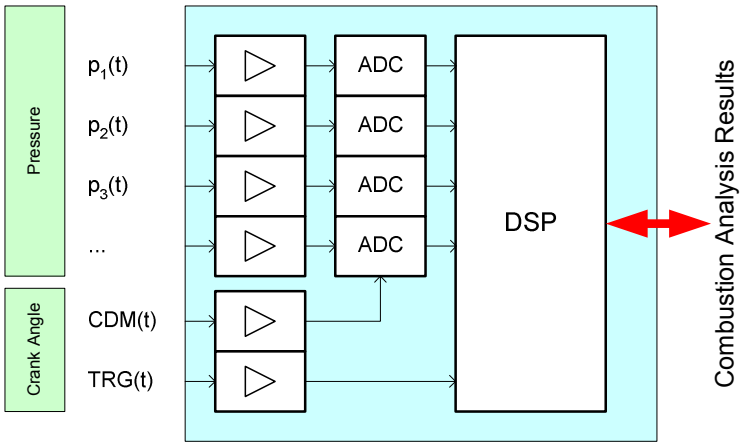

Figure 1: Structure of a combustion analysis system

Data acquisition / evaluation: In the systems now in common use, the pressure signals are sampled on the basis of the crank angle and the combustion analysis values are calculated accordingly. The layout shown in Figure 1 has the disadvantage that the sampling frequency varies with engine speed. This means that it is more difficult to obtain typically time-related evaluations (e.g. filtering and spectral analysis).

3. In-Vehicle Combustion Analysis

The environmental and operating conditions of an in-vehicle combustion analysis system differ significantly from those of an engine test stand. The main requirements of an in-vehicle combustion analysis system may be summarized as follows:

- compact design
- resistant to harsh operating environment conditions
- use of engine-mounted crank angle position device
- operation with vehicle supplied electrical power
- fast and simple installation
- easy parameterization and operation
- reliable acquisition of measured values, even with transient engine operation
- simple integration into the calibration system

Unlike typical engine test stand operating conditions, transient engine operating states are predominating on the road. With the use of an in-vehicle combustion analysis system, it is important for the calibration engineer to be able to assign the combustion analysis values to the engine control variables with high certainty. Only then it is possible, for example, to identify a direct relationship between interventions of the engine controller (cause) and misfires (effect). This means that the integration of the in-vehicle combustion analysis system with the engine calibration system is an essential precondition for engine calibration and trouble-shooting to take full advantage of in-vehicle combustion analysis.

Mounting of cylinder pressure sensors

The deployment of in-vehicle combustion analysis technology is generally characterized by poor accessibility and restricted space for the components to be mounted. Mounting must be both time-saving and adapted to the harsh operating conditions in the engine compartment. In addition, it is important that the operation of all components should be simple and should not require any great efforts for parameterization. The use of measuring spark plugs [1] and glow plug adapters (see Figure 2) permits high precision combustion pressure sensors to be mounted in the existing combustion chamber access points without need for additional preparation work.

Figure 2: Measuring spark plug and glow plug adapter with sensor for the measurement of combustion pressure

Engine-mounted crank angle position device

The installation of an optical crank angle encoder for an in-vehicle engine has generally been very time-consuming. However, now that all vehicle engines are supplied with a trigger wheel and a Hall or inductive sensor to acquire the crank angle position for electronic control purposes, it is possible to use this crank angle position device also for the purpose of in-vehicle combustion analysis. Figure 3 shows a typical 60-2 trigger wheel with a Hall sensor. With a 60-2 trigger wheel, there is a resolution of 6°CA or 18°CA at the mark gap. The gap is for synchronization. As a rule, engine combustion analysis requires a crank angle resolution of 0.1°CA. To increase this resolution by a factor of 60 or 180 while ensuring a high degree of reliability, even under transient engine operation, is a demanding task.

Figure 3: 60-2 trigger wheel with Hall sensor

Interfacing with the engine calibration system

The objective of engine calibration is the optimization of the control and regulation functions and the programming of the engine control unit. Parameterization is carried out on the basis of operating maps, characteristics and parameters. In order to interpret and optimize these parameters, countless electrical and physical values are measured on the test stand as well as on the road and are subsequently evaluated. Many of the calibration target values depend heavily on combustion. The characteristic combustion analysis values permit a rapid identification of the corresponding setting parameter and the direction and size of the necessary adjustment. Figure 4 shows the coupling of the analysis system and the INCA calibration system via the INCA open hardware interface (OHI). This arrangement ensures that first class results are obtained much easier and quicker.

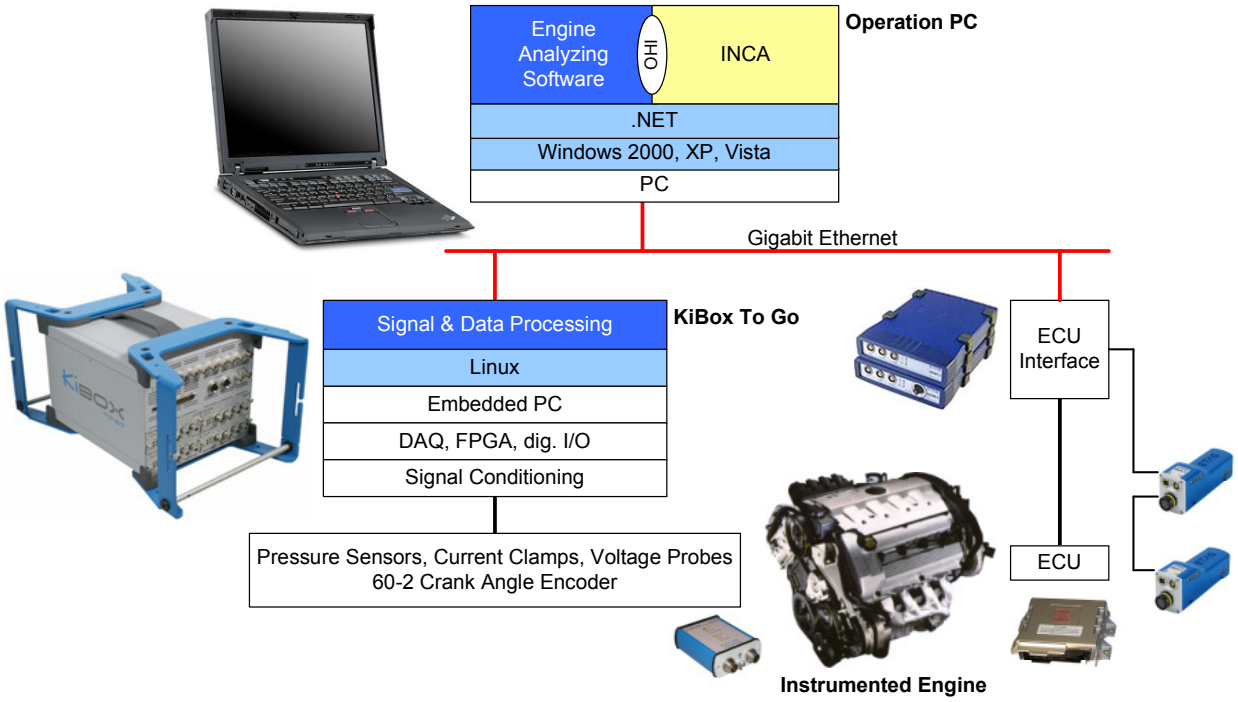

Figure 4: Interfacing of the combustion analysis and engine calibration system

4. KiBox Data Acquisition and Evaluation

For in-vehicle combustion analysis data acquisition has to fulfill special needs. For example: the engine-mounted crank angle position device has to be continuously monitored. At the same time, the highly transient engine operation must be measured and the naturally present signal interference must be accounted for.

In 1991, Kistler began developing the first control monitor device for integrated process monitoring in manufacturing. The CoMo II digital measuring system records two time-discrete measurands. In press-fit processes, for example, this includes press force and displacement. The transformation for the force versus displacement evaluation as well as the display of the measurement data and cycle-related values takes place in real-time. Since the first version, several generations of Kistler's Como devices, some of them with more than two channels, have been brought into the market worldwide. These devices permit universal parameterization and are deployed for the monitoring of processes of all kinds. For this purpose, sampling rates of up to 10 kHz are sufficient.

The principle of time-discrete sampling is ideally suited to fulfill the requirements of a modern combustion analysis system. It permits the correction of phase shift of measuring signals, signal filtering in the time domain and the transformation of measuring signals into the angle domain. Due to the high engine speeds and the high precision required, extremely high sampling rates are needed. Commercial availability of very powerful data acquisition and data processing devices now made it possible to

build a compact combustion analysis system for in-vehicle operation using this principle.

Data Acquisition

The central requirement of multi-channel data acquisition systems is that the analog signals – in the present case, the cylinder pressures, the injection signals, the ignition signals and the crank angles – have to be acquired simultaneously and in-phase with the least possible delay. Otherwise, it is impossible to obtain correct comparisons and calculations. Even signal run time differences of two to three microseconds can have a considerable impact on the quality of the results. To avoid aliasing effects, bandwidth limitations are placed on the analog measuring signals prior to the analog to digital conversion. The Shannon theorem is taken into consideration in the digitization of the analog measuring signals. Figure 5 provides a schematic representation of the data acquisition structure.

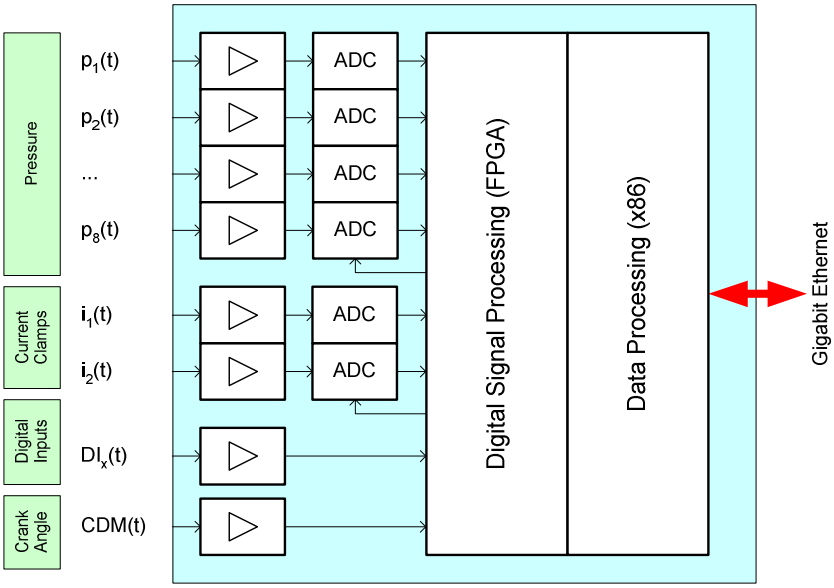

Figure 5: KiBox data acquisition and processing

Signal and Data Processing

After digitization, the individual delay times of all the measuring signals are corrected. The absolutely synchronous measuring data are then interpolated on a crank angle resolution of 0.1°CA (Figure 6). As the interpolation is always executed after the acquisition of a full angle increment (with a 60-2 trigger wheel there is a regular 6°CA or 18°CA at the gap), a correct interpolation is simple. This takes into consideration the irregularity of angular speed of the engines crankshaft. A stream of time and crank angle resolved data is thus available for the calculation of the combustion analysis values. Where necessary, the analog measuring signals can also be filtered on a channel-specific basis using a digital low pass filter before the angle data are generated and, as the time delay of the low-pass filter is known, it can be eliminated easily. As a result, it is possible to have in-phase suppression of interference signals (e.g. from pipe oscillation, or valve impact as shown in Figure 7).

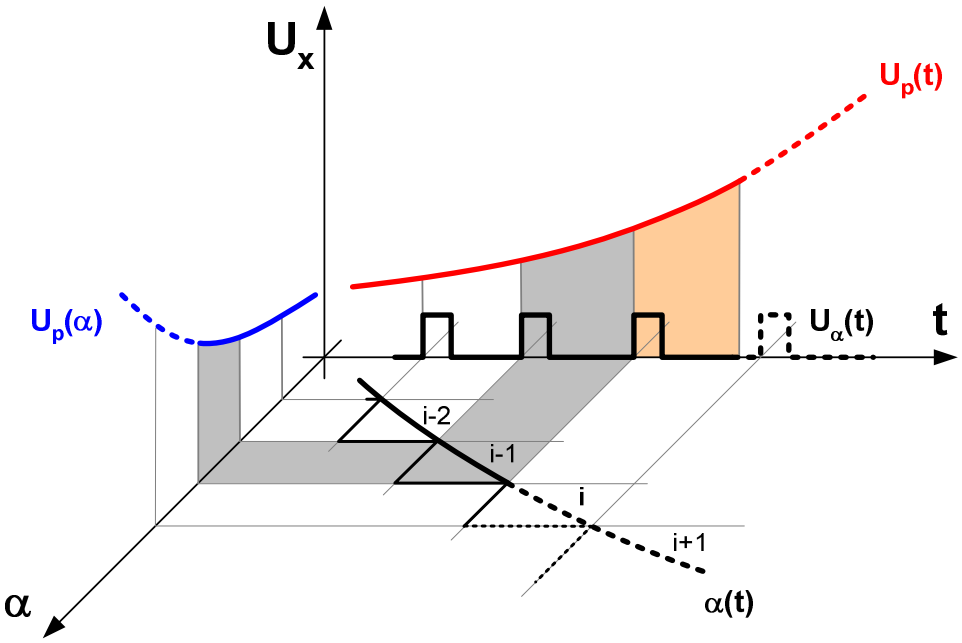

Figure 6: Measurement data transformation of time domain to the angle domain

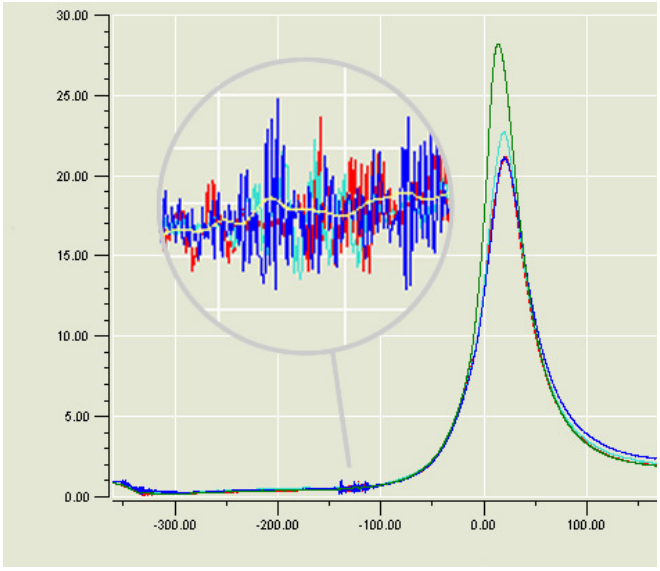

Figure 7: In-phase elimination of valve impact interference with low pass filter (yellow curve)

Data Evaluation

The evaluation of the measurement data supplies engine developers with the vital combustion analysis values in real-time. The standard characteristic values can be obtained from the cylinder pressure curve p(t) and p(α):

- mean effective pressure IMEP, PMEP and NMEP
- peak pressure p_{max} and its crank angle position $\alpha(p_{max})$

- energy conversion (heat release), start of combustion, 50% mass fraction burned (MFB) and duration of combustion
- increase in pressure dp/dα, dp/dt plus maximum increase in pressure and its crank angle position
- combustion noise
- assessment of combustion stability: cycle-to-cycle variation and individual differences between cylinders
- knock analysis

Through the additional acquisition of injection and ignition timing signals, it is possible to optimize the injection angle InjA(α) and injection duration InjD(Δα) or InjD(Δt) and ignition angle IgnA(α). If intake and exhaust manifold pressures are measured as well, the gas exchange process can also be analyzed.

5. System Parameterization

In view of the need for fast and simple mounting and ease of operation, it is clear that parameterization plays a crucial role. The use of sensors with integrated transducer electronic data sheet (TEDS) permits automatic parameterization of the whole measuring chain. The sensor characteristics stored on an integrated memory are transmitted to the amplifier modules and all of the relevant parameters are set automatically. For example, in the case of cold start testing under very cold conditions when the acquisition system has to be installed and removed frequently and correct parameterization of the whole measuring chain is essential from the first attempt, TEDS ensures the avoidance of erroneous results due to incorrect parameterization. Further functions of the TEDS can also be used, such as the acquisition of the sensor operating hours for purposes of quality assurance and resource management.

The entry of specific engine parameters (bore, stroke, piston rod length, etc.) can be accomplished by reading pre-defined files or direct entry via the graphical user interface (GUI), as the one illustrated in Figure 8.

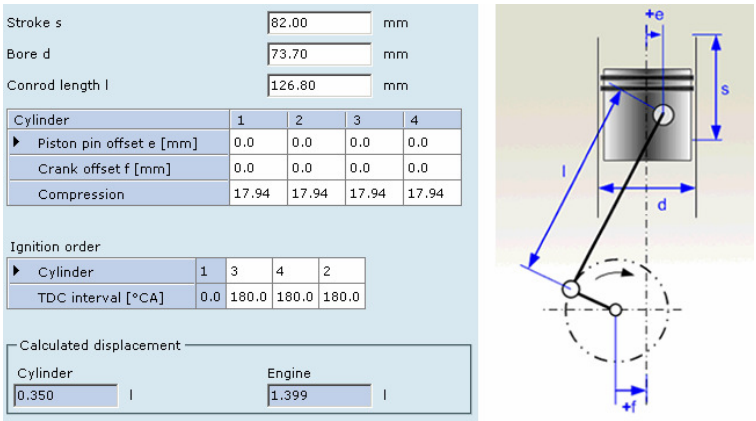

Figure 8: GUI for engine parameters

As shown in Table 1, accuracy of most combustion analysis values show a strong dependency on the synchronization between the individual combustion pressure values and the associated crank angle values. The slightest error in the assignment of the correct top dead center (TDC) reference point can cause unacceptable errors. For example, an incorrect angle assignment of 1°CA at an indicated mean effective pressure of 10 bar can generate a NMEP error of 0.3 bar. The approximate percentage error over the NMEP stands at around 3%.

Combustion analysis values	**Accuracy TDC reference point**
Peak pressure p_{max} (peak-peak)	No need, except cycle identification
Peak pressure $\alpha(p_{max})$	Average accuracy (≤0.5 °CA)
Ignition angles	Average accuracy (≤0.5 °CA)
NMEP, and statistics for NMEP (misfire, cycle-to-cycle variation)	High accuracy (≤0.1 °CA)
Beginning of injection (for DI)	High accuracy (≤0.1 °CA)
Beginning of combustion, 50% MFB	High accuracy (≤0.1 °CA)
Average frictional pressure FMEP	High accuracy (≤0.1 °CA)
Knocking intensity	Low accuracy because the TDC reference point is necessary only for determination of the evaluation window
Combustion noise level	No need, except cycle identification

Table 1: Combustion analysis values versus TDC reference point accuracy

6. Use of In-Vehicle Combustion Analysis in the Engine Calibration

This section presents a number of examples of the use of in-vehicle combustion analysis for engine development and engine control calibration.

Cold Start

The optimization of the few individual working cycles when starting the engine is important to ensure a high degree of operating reliability and low degree of pollutant emissions. This means that combustion analysis is a vital necessity for the determination of cycle resolved measurement of the starting process [2]. An evaluation based on external sensors is, in principle, inadequate due to the distance from the process, low time resolution and lack of time versus working cycle reference. The evaluation is confined exclusively to visual assessment in the crank angle domain by considering pressure curves in combination with the actual engine speed and the injection or ignition timing.

For the assessment of combustion, it is essential to know the combustion efficiency [3], which relates the quantity of fuel supplied to the quantity of fuel actually burned per working

cycle. In addition, the current engine speed and the NMEP trend over the working cycles are used to assess the idle quality of the engine.

Drivability

The optimization of drivability requires tuning between the driver's torque requirement (accelerator pedal position) and the reaction of the engine (NMEP). What is sought is the smallest possible delay in implementing the driver's torque requirement. The criterion for the build-up of torque is the increase in NMEP per working cycle taken from the combustion analysis, as exemplified in Figure 9. The accelerator pedal position is shown in black, the throttle position in blue, the engine speed in green and the NMEP curve during an acceleration process in red.

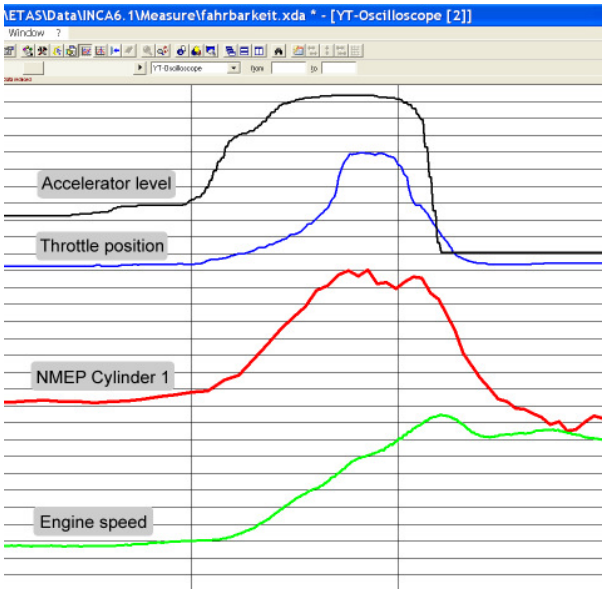

Figure 9: Illustration of acceleration in the INCA system

Through overshoots, transient on-road operating conditions harbour the potential to generate critical safety conditions that do not arise under normal test-bed operation. Typical examples of this are peak pressure being exceeded or heavy knocking in individual working cycles. These conditions can be quantified and analyzed only with the help of combustion analysis and reduced or avoided altogether through the proper adjustment of the control parameters.

Trouble-shooting

Mobile combustion analysis is an extremely valuable tool for rapid combustion analysis and safeguarding of the calibration in trouble-shooting during on-road trials. The transfer of the combustion analysis values into the INCA calibration system and the synchronous display of the working cycle with engine control parameters permit fast and efficient identification of malfunctions and perturbations.

The synchronous display of the pressure and heat curve facilitates trouble-shooting with engine problems (e.g. compression or injector problems). This display is particularly useful

for the optimization of combustion parameters during on-road trials. Modifications in the calibration data of the engine and associated effects on combustion stability, are immediately displayed and quantified. In the case of diesel engines, for example, the strategy for the regeneration of a particle filter is quickly optimized (definition of injection timing).

It is also possible to quickly detect any inaccuracies in the calibration data set (e.g. consideration of cylinder pressure and exhaust gas temperature before turbo charger) or to check the calibration data set of the engine under dynamic operation and test drives in hot/cold regions, or high/low altitudes, or in operation with a trailer. The ECU values and the combustion analysis results are inherently synchronized within each engine cycle, providing immediate results to the display without the need for manual synchronization.

7. Summary

KiBox, the new combustion analysis system from Kistler Instrumente AG, was developed particularly for in-vehicle operation. Under real driving conditions, the system provides the ability to execute combustion analysis in real-time and provides combustion analysis data with a high degree of accuracy. Due to the use of the engine-mounted crank angle position device and interpolation of the intermediate crank angle values, the crank angle information is presented with high precision and low mounting costs. The integration of KiBox into the INCA calibration system ensures that the combustion analysis values can be displayed and analyzed simultaneously with the engine control actuating values. In short, KiBox represents a mobile combustion analysis tool that ensures a highly efficient method of working both for engine calibration and for trouble-shooting.

References

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