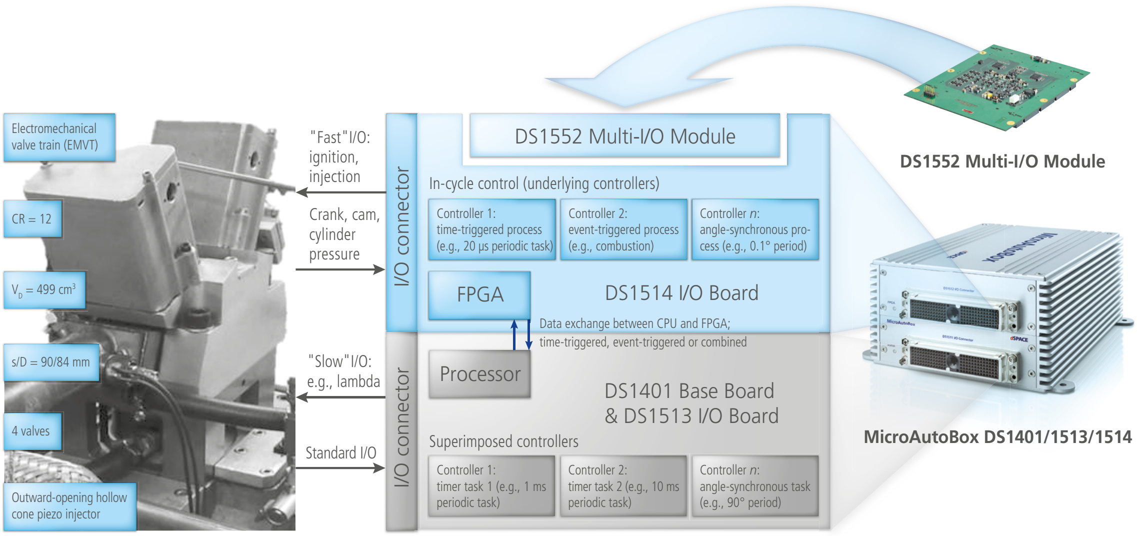
The development of innovative combustion processes for engines often demands extremely fast control loops that enable engineers to intervene even in an ongoing combustion process. RWTH Aachen University used a dSPACE MicroAutoBox II for an in-cycle control to ensure a stable and controlled autoignition for gasoline engines.

When thinking about alternative propulsion technologies, developers nowadays tend to focus merely on the aspect of electromobility. This can be shortsighted when it comes to combustion engines, which are sometimes regarded as phase-out models, but whose development potential is far from being exhausted. New and innovative combustion processes promise a considerable increase in efficiency. Autoignition, for example, which was previously a monopoly of diesel engines, can also be employed in gasoline engines. Gasoline controlled autoignition (GCAI) is expected to significantly reduce emissions of carbon dioxide, nitrogen oxides, and particulates. However, implementing GCAI requires complex control and regulation processes. For this reason, closed loops using an indicated combustion chamber pressure as an input value have proved to be particularly promising. A direct and thermodynamic analysis of the pressure curve enables developers to immediately evaluate combustion and adjust in-cycle setpoints. Researchers at the Institute for Combustion Engines (VKA) of RWTH Aachen University are engaged in finding methods of rapid control prototyping that ensure an adequately fast in-cycle control with integrated index analysis and with minimum latencies.

Highly Variable Research Engine

For this, the researchers in Aachen use a single-cylinder engine with direct injection and an outward-opening piezoelectrically actuated hollow cone injector in a central position (figure 1). The research engine is further equipped with a fully variable electromechanical valve train (EMVT). Because the valve train can be disconnected completely from the crank drive, it is possible to specify the high proportion of internal residual gas required for autoignition for each cycle and according to the operating point. dSPACE's MicroAutoBox II together with its freely programmable Xilinx® Kintex®-7 FPGA has proved to be an ideal develop-

Figure 1: Single-cylinder research engine with an electromechanical valve train (on the left); Development ECU MicroAutoBox II with Kintex-7 FPGA (on the right).



ment ECU for the planned research work. For the first time, the institute used the XSG Advanced Engine Control Solution with MicroAutoBox II. The solution is an open library, designed for a model-based FPGA design from within Simulink® and based on Xilinx System Generator (XSG).

Real-Time Indication

A characteristic feature of the solution is its real-time-capable evaluation and cylinder pressure indication (CPI). The crankshaft, camshaft and encoder signals are first evaluated on the FPGA by an angular computation unit (ACU), and an angle signal with a resolution of 0.1° is generated as a basis for further real-time evaluations. The cylinder pressure signals are sampled at 1 MHz and processed crank-angle-synchronously. During this process, the thermodynamic values required for the in-cycle control are specified, such as the heat release behavior, the indicated mean effective pressure of the high-pressure loop and the gas exchange, as well as the peak pressures and pressure gradients. To ensure real-time capability, only causal algorithms are used. In a comparison test, the algorithms of the CPI used were validated via the well-established indication tool Combustion Analysis System (CAS) of FEV GmbH. With less than one percent, the occurred deviations were negligibly small, so that the parameters required for an in-cycle control can be provided at the rate of the FPGA. The fast actuators (EMVT, fuel injection) are also controlled directly via the XSG Advanced Engine Control Solution, enabling control intervention within just a few nanoseconds. Thus, it can be performed within one combustion cycle and serve as a correction variable for the slow and global control that was implemented on the processor unit of MicroAutoBox II.

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Firing up Engine Innovation

In-cycle combustion control for autoigniting gasoline engines

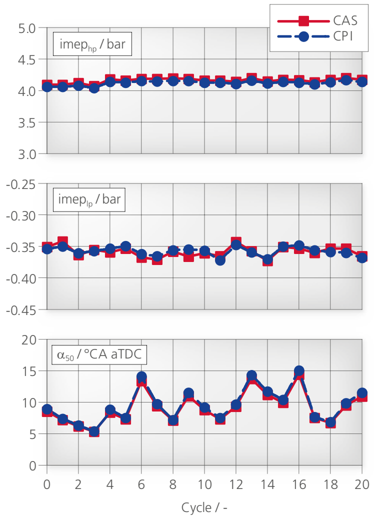

Figure 2: Exemplary comparison of the cylinder pressure indication (CPI) via the Advanced Engine Control Solution and via the tool Combustion Analysis System (CAS). The deviations of the indicated mean effective pressure imep_{hp} *and* imep_{lp} *as well as of the center of combustion (*α_{50}*) were negligibly low.*

In-Cycle Control Concept

During the research experiments, the high proportion of internal residual gas required for autoignition was realized by means of combustion chamber recirculation. In this approach, the exhaust valve is closed early and the intake valve opens late, symmetrically to the top dead center of the gas exchange. During this phase, the exhaust gas remaining in the combustion chamber is compressed. As a result of the unburned fuel, a late and incomplete combustion is typically followed by an early combustion with a high pressure increase. There is a clear correlation between the pressure level during intermediate compression and the subsequent point of combustion. An extremely late combustion therefore leads to a significant heat release during intermediate compression (figure 3). This correlation was used in an in-cycle control. The Advanced Engine Control Solution was employed to determine the maximum cylinder pressure signal during intermediate compression, which serves as an input signal for the control loop. The crankshaft angle at which the intake valve closes is used as a control variable (IVC in figure 4). Delaying this action reduces the effective compression ratio. Consequently, the conditions for autoignition and the center of combustion are also delayed. Closing the intake valve earlier encourages autoignition and therefore results in an early center of combustion. If the real-time evaluation of the cylinder pressure performed during intermediate compression reveals a low peak pressure at the top dead center of the gas exchange, the control variable for the closing intake valve is moved to an earlier point within the same cycle, in order to prevent a late center of combustion, and vice versa. As a result, the control loop closes between the top dead center of the gas exchange and the activation of the intake valve, within a crankshaft angle of approximately 90° CA, which corresponds to a time slot of 10 ms at a rotational speed of $n = 1500\ \text{min}^{-1}$.

> “dSPACE’s tools enable extremely fast in-cycle control, opening the door for the development of innovative combustion processes.“
>
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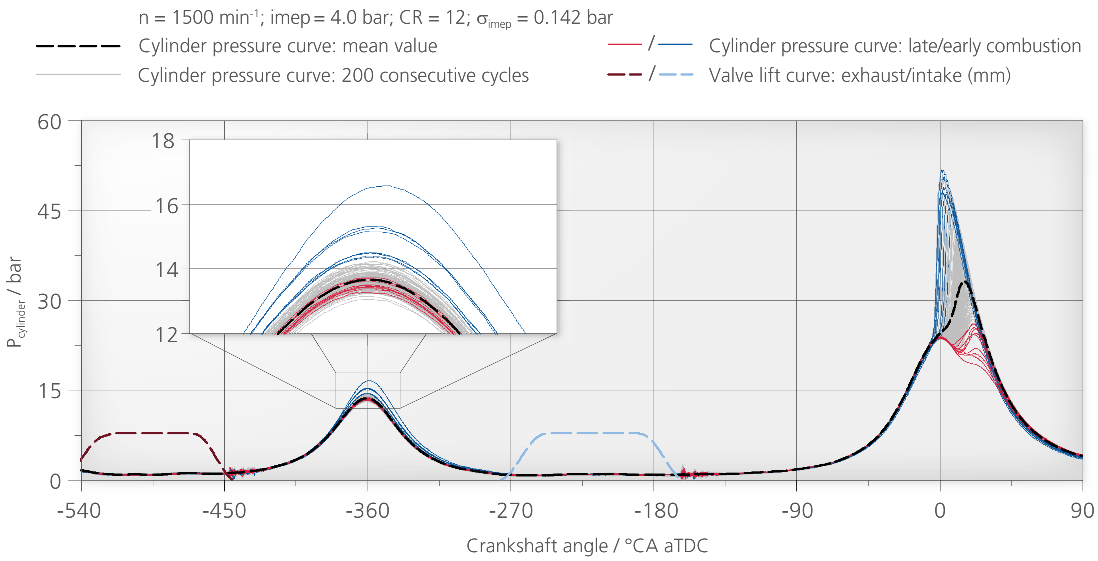

Figure 3: Cylinder pressure traces with a late (red) or early (blue) combustion point. The cyclic fluctuations that are quantified by a high standard deviation of the indicated mean effective pressure σ_{imep} = 0.142 bar, are clearly visible.

Convincing Results

Evaluations of the described in-cycle control clearly reveal that extreme load deviations can be avoided by an active control, which considerably decreases the standard deviations of the indicated mean effective pressure (figure 4). The center of combustion also improves significantly. An extremely early or late center of combustion can be avoided reliably. By using the correlation between intermediate compression and subsequent combustion, the researchers of the RWTH Aachen University successfully implemented the intended in-cycle control and use it with the research engine. The potential of fast control interventions became evident. Further research projects of the university will aim at using the capabilities of the FPGA of MicroAutoBox II for even more complex control algorithms. By this, the researchers seek to optimize the prediction of the combustion process via the real-time evaluation of cylinder pressure. There is also a need for further research in the area of control variables that allow control interventions within an ongoing cycle. In this context, the Institute for Combustion Engines is presently scrutinizing strategies for multiple injection and water injection, in particular. So there is a good chance that the internal combustion engine will not become a phase-out model after all. ■

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Figure 4: IVC (control variable for the closing intake valve), α_{50} and imep, for 1000 consecutive cycles with an active and inactive in-cycle control. With an active control, the standard deviation of the indicated mean effective pressure decreases considerably from σ_{imep} = 0.142 bar to σ_{imep} = 0.088 bar (at the bottom). An extremely early or late center of combustion can be avoided reliably (center).