

Control of the Diesel Combustion Process via Advanced Closed Loop Combustion Control and a Flexible Injection Rate Shaping Tool

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ABSTRACT

The presented paper deals with the set-up and performance of a newly developed control system as well as with achieved engine results. This control system is able to control the entire cylinder pressure trace by using a flexible rate shaping injector and iterative learning control (ILC). Standard thermodynamic cycles, like isobaric and Seiliger cycles, and a newly suggested class of cycles are generated and analyzed on a single cylinder engine. With this control system an extremely flexible tool for optimization of combustion processes is available to exploit the full potential of injection rate-shaping on diesel engines.

INTRODUCTION

On the market an increased introduction of injection systems with rate-shaping capability can be observed [1]. These injection systems manipulate the injection rate and therefore simultaneously the combustion of direct injection diesel engines by needle lift or modulation of injection pressure. An improvement of exhaust emissions using rate-shaping is already published in several papers [3, 7]. Similar to rate-shaping, closed loop combustion control increases its market penetration to an even higher degree [5]. Thereby information about the combustion is measured with a pressure sensor in the combustion chamber and is processed by control algorithms in a way that the desired output values are reached by manipulating the inputs. All these closed loop combustion control systems share the fact that only characteristic values, e.g. center of combustion, are

calculated from the pressure trace and only individual variables of the injection, e.g. start of main injection, are influenced [4].

As a consistent further development of these two trends, the following paper deals with a combination of both topics which, for the first time allows to control the entire cylinder pressure trace by using the flexible injection rate-shaping tool (FIRST) developed by FEV Motorentechnik GmbH [15]. Calculation of characteristic values is (nearly) entirely omitted. With this control system direct presetting and control of the combustion process output is possible. A peak pressure limitation is performed simply by limiting the desired pressure trace to a maximum value. The required injection rate for this limitation is generated by the control system.

The control system fully utilizes all information of the cylinder pressure trace and performs an experimental system inversion by using iterative learning algorithms to generate arbitrary output traces of cylinder pressure. The above mentioned system inversion leads to a completely new view on optimization of combustion processes. Up to now only inputs of the combustion process, like the start of injection or rate-shape are varied. Now a defined thermodynamic process can be directly preset and influences of this process on exhaust emissions can be analyzed.

Disturbance variables, like EGR-rate, could be compensated by the control system. The engine load (IMEP) is controlled by a separate governor. Furthermore, new cycles are suggested to optimize the

combustion process and to show the various possibilities of this new closed loop combustion control system.

The presented paper deals with the set-up of the control system, including the control theory of iterative learning control and controller design. After introducing a new class of thermodynamic cycles, the α -process, the controller and the combustion process performance achieved with the control system are discussed. The emission results for the isobaric, the Seiliger and two kinds of α -processes are given for one specific speed/load point. First conclusions for the different emission results are presented.

MOTIVATION

As already known from various publications, the development of the cylinder pressure can be controlled via injection rate shaping in such a way as to realize nearly isobaric combustion [17]. A real-time system is already developed at VKA, which can calculate the necessary injection rate for isobaric combustion during a combustion cycle [8]. Other combustion processes can be produced with this system only with large effort. Due to the real-time processing and the intervention in the active cycle the system needs tremendous computing power. In addition to a universally valid approach to forming desired combustion processes, the required computing power must be reduced in the course of the development of the control system described in this paper. The results of the already existing system are used in the development of the new concept and extended with more experiments.

For the development of the new concept the question arose whether it is possible to generate this cylinder pressure profile without a real-time system. With the knowledge of the required input signal for the FIRST injector the realization of the specified cylinder pressure behavior is possible.

The experiment illustrated in figure 1 covers the transition from normal rectangular injection to an injection for isobaric combustion. The real-time system is able to realize this transition within one cycle during the operation of the system. A control system with less processing power will not be able to perform this transition so fast and will need intermediate steps between the injection rate profiles. The required processing power will then be distributed over multiple cycles. The question that arises is, whether such a transition is stable without a real-time system. During the experiment each of the four intermediate steps is reached by morphing the injection profile into the shape of isobaric combustion. The injection profiles are open loop controlled without any cylinder pressure feedback.

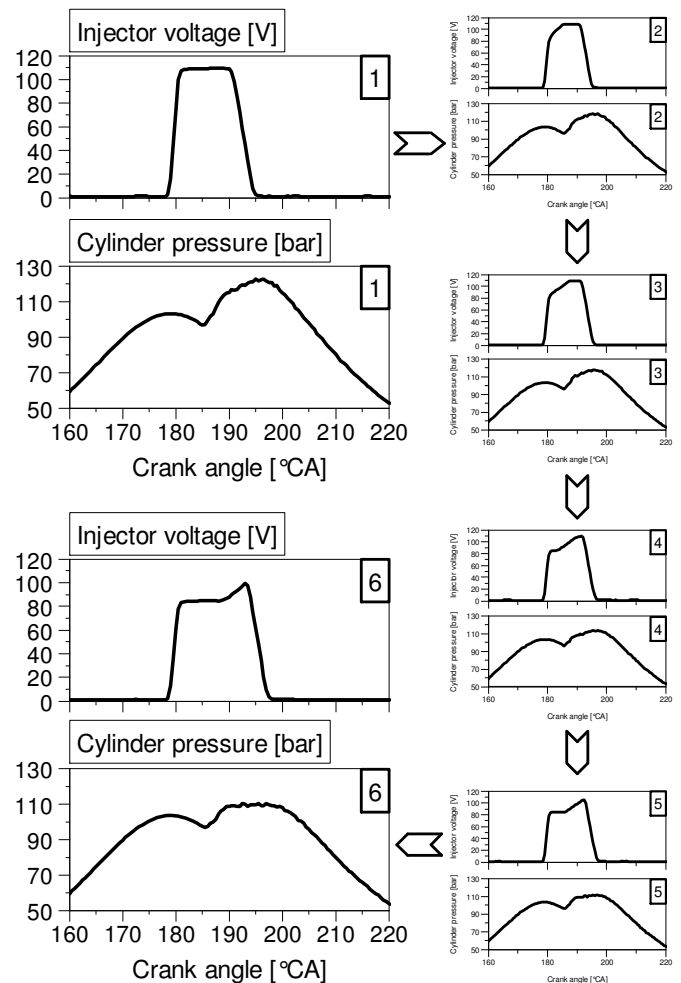


Figure 1: Open loop controlled transition from rectangular injection rate to an injection for isobaric combustion with 4 intermediate control steps

It can be seen in figure 1 that all intermediate steps are stable. Furthermore, it can also be seen that the cylinder pressure profile follows this transition. With every further step, it becomes more similar to the isobaric combustion. The deviation from the pure isobaric combustion in the shown cylinder pressure trace is a result of a late start of injection, which is too late to achieve perfect isobaric combustion. The trial shows that the transition can be realized in a stable way without a real-time system and does not have to be performed in one step.

A good candidate to perform this task is an iterative learning control (ILC). This type of control algorithms iteratively improves the control result until the desired output trace is reached. Therefore a high number of iterations are necessary. However, only minimal knowledge of the plant is needed to set-up an ILC due to the fact that the control algorithm is "learning" how to handle the plant.

Especially in the topic of the combustion process development at stationary operating points 20 or more cycles often follow each other in one second and the transient response of the combustion process is of

subordinate interest which is very advantageous for ILC algorithms. ILC is combining good setpoint tracking accuracy with low effort for setting up the control system, but still has a high degree of flexibility regarding setpoint traces and engine operation points. For these reasons ILC was chosen in this paper as control algorithm.

ITERATIVE LEARNING CONTROL

Iterative learning control algorithms were developed in 1984 to improve the operation of robots [2]. Later on ILC was used to control a wide variety of plants like e.g. vibration test benches for fatigue tests [13] and cyclic production processes like extruders [11]. However the application to cylinder pressure control of Diesel engines is not yet observed.

Mathematically seen, the iterative learning control illustrates a stepwise experimental process inversion. The actuating variable of the process will be modified from cycle to cycle until the desired output value is reached. During a cycle open loop control of the process takes place. The actuating variable for the whole cycle is calculated offline from the results of the previous cycles and then is used for the actuation of the system. By using the feedback from previous cycles a closed loop control across cycles is generated [13]. ILC is realized with an open loop control in combination with a memory element. The analysis of the memory as a whole takes place between cycles, i.e. a pause must be available between cycles. This pause is only limited by the required calculation time for the generation of the actuating variable. With low calculation complexity, this pause time can become very short or vanish completely. In this case, the structure of a repetitive controller is obtained which is also configured for a high number of process repetitions. Such a repetitive control system for example was applied to control the smoothness of a diesel engine [9].

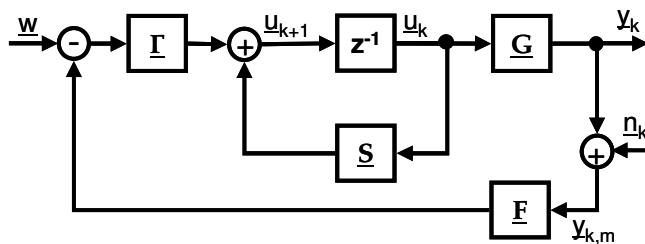


Figure 2: Time domain ILC control structure

In figure 2 the structure of the ILC is shown. The central memory z^{-1} can be seen, which separates the actuating variables of two consecutive cycles $\underline{u}_k$ and $\underline{u}_{k+1}$ from each other before they are applied to the plant $\underline{G}$. The noise affected feedback $\underline{y}_{k,m}$ for the generation of the cycle to cycle closed loop control is also shown. The actuation signal for the next cycle

$$\underline{u}_{k+1}(i) = \underline{S}\underline{u}_k(i) + \underline{\Gamma}_P \underline{e}_k(i) \quad (1)$$

is generated from the actuating signal vector of the previous cycle that is weighed with the actuating variable filter $\underline{S}$ and the control deviation which is weighed with the learning operator $\underline{\Gamma}$. The control error

$$\underline{e}_k(i) = \underline{w} - \underline{y}_{k,m} \quad (2)$$

is calculated from the setpoint vector $\underline{w}$ and the feedback of the actual cycle. Equation 1 forms the core of the ILC and therefore is named the learning rule, as the learning procedure is processed here. The learning operator is therefore taken as constant for all cycles. In this way the ILC differs from an adaptive controller where the learn operator or the controller parameters are adjusted on the current system (or system model).

The illustrated learning rule is a P- or Proportional-ILC which represents the most commonly utilized type of ILC. This is the simplest and therefore the most easily understandable form of ILC. For this work, however, a variation of D- or Differential-ILC

$$\underline{u}_{k+1}(i) = \underline{S}\underline{u}_k(i) + \underline{\Gamma}_D \underline{e}_k(i+1) \quad (3)$$

is used to be able to emulate the time-variant ignition delay. From equation 3, it is obvious that for a D-ILC, acausal data processing is a necessity, i.e. all data from the actual cycle must be available at the time of processing.

When figure 2 is compared with the state space representation of a time-discrete linear time independent system (LTI-system) some similarities are obvious. For example, the actuating variable vector of an ILC corresponds to the state vector of a state space representation. This is not surprising, since an ILC is a change of state from one cycle to the next. The learning rule of the ILC, as already implied in the derivation, takes the place of the governor. One disadvantage of the ILC will be obvious when the dimensions of the matrices are compared; the ILC of a SISO¹ system is equivalent to a MIMO² state space representation. This has a huge impact on dealing with an ILC. For example, the matrices used in equations 1 and 3 have a dimension of N by N, where N is the number of samples of one cycle. However, for the practical implementation, it has a rather less important role as the simplicity of the design is not compromised. But also the biggest advantage of the ILC is visible within this comparison. At the spot where in the state space representation the system matrix is placed, in ILC the already introduced actuating variables filter is placed. The actuating variables filter, however, does not include system information at all, whereas for the system matrix a (more or less known) model of the system must

¹ Single Input Single Output

² Multiple Input Multiple Output

be available. ILC therefore can be designed and operated with minimal system knowledge. This, on the other hand, clearly distinguishes the ILC from an optimal control governor. For this type of control, detailed knowledge of the process is required and the calculation of the actuating variables is performed with the help of complex algorithms. By means of the iterative approach of the ILC, it is possible to utilize simpler algorithms and at the same time to reach comparable results (at least after some time). Also ILC has the advantage that it can adjust to a changing system due to the robust design.

Equation 3 shows that a complete learning is only possible when the complete information from the previous cycle is taken over for the current cycle. The actuating variable filter must then be constructed as

$$\underline{S} = \underline{I} \quad (4)$$

so that the ILC can reach full noise suppression and stationary accuracy. The controllability and observability are analogous to a state space representation. They can be studied for example in [13].

INJECTOR AND SYSTEM SETUP

The system setup and signal flow is shown in figure 3. At the single-cylinder engine (specifications are given in table 1) the cylinder pressure is measured with a piezo-electric pressure transducer. The calculation of the control algorithm is done in a rapid control prototyping (RCP) system by using the measured crank angle signal and the amplified pressure transducer signal. The resulting injector voltage of the control algorithm is amplified by a power stage and then fed to the injector which injects the fuel into the engine.

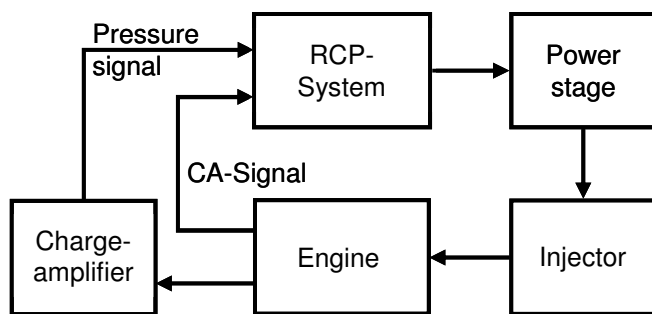


Figure 3: Signal flow and components of the control system

The FIRST injector was developed by FEV in cooperation with the Institute for Combustion Engines, Aachen, to be able to investigate the full potential of injection rate shaping without having parasitic side effects by nozzle seat throttling. The injector is a common rail type which is actuated by a piezo actuator. The FIRST allows modeling any kind of injection shape by varying the injection pressure at fully open nozzle

needle. An additional advantage is a very fast opening and closing of the needle, which reduces the nozzle seat throttling effects to a minimum compared to current series production injectors. Detailed descriptions of the FIRST can be found in [15]. Specifications of the used nozzle are given in table 1.

Table 1: Specifications of engine and nozzle

Engine	
Number of cylinders [-]	1
Number of valves [-]	4
Bore [mm]	81
Stroke [mm]	88
Displacement [cm ³]	453
Compression ratio [-]	15.8
Swirl [cu/ca @ max. valve lift]	1.7
Nozzle	
Cone angle [°]	153
Hydraulic flow rate [cm ³ /30s]	320
Hole number [-]	8
Nozzle k-factor [-]	1.5

GOVERNOR DESIGN

For the application to the cylinder pressure control the ILC algorithm has special requirements for the acquisition and processing of the cylinder pressure data and therefore also for the indication system that is used. The main requirements are the following:

1. Capability to process the data "offline"
2. Variable sampling times for different phases of the engine operation

Furthermore, additional functions have to be fulfilled, for example correct synchronization of data, calculation of characteristic values or determination of the absolute pressure. Requirement 1 is indeed present in all common indication systems, but is mostly designed for the recording of data. Access to all the data of one engine cycle is necessary for the developed control strategy. With existing indication systems the pressure data can only be stored on hard drive and not be accessed by the user during engine operation, so a new indication system was developed, which can realize this function in real-time.

The aim of this is to have the complete measurement data of the high pressure phase (stored as a data vector) ready for calculations directly after the completion of the high pressure phase. This has the advantage that a complete engine revolution (during the low pressure cycle) is available for the calculation of the control algorithm and the newly calculated control values can

already be applied in the next high pressure phase. To avoid additional calculation time losses caused by data transfer the control and the indication system are designed as one unit on the same RCP-system.

With a single cylinder engine, high cyclic fluctuations occur due to the construction. As the control algorithm “learns” over multiple cycles, the consideration of these fluctuations for the calculations is not desirable. A suitable possibility to reduce this fluctuation is to average the pressure vector over multiple combustion cycles. In the present paper, an averaging over 20 cycles is used, i.e. one control cycle is equal to twenty engine cycles. Unfortunately, this averaging does not reduce the high frequency noise, for example sensor noise, sufficiently. For that purpose, an additional acausal averaging filter

$$H(z) = \frac{1}{2m+1} \sum_{k=-m}^m z^{-k} \text{ with } m \in [1, 2, 3, \dots] \quad (5)$$

must be used. This acausal filtering reduces the high frequency noise without causing a phase shift. For the calculation of equation 5, “offline” processing of the data is also needed (requirement 1).

Due to different limitations regarding the computing power and the memory management of the RCP-hardware a reduction of measurement data is needed. Principally, two different sets of measurement data are needed (requirement 2). One dataset, consisting of a pressure vector and an actuating variable vector, is necessary for the control algorithm. This dataset must have high resolution to produce a good result of the ILC. A too coarse resolution would cause an insufficient adjustment of the setpoint vector due to the reduced degree of freedom. For the dataset with high resolution only the ILC relevant area from the beginning of the injection until the end of combustion is necessary. This area is defined as the fixed crank angle range from 160 °CA to 220 °CA. A larger area will only cause a large amount of unnecessary data and accordingly produce problems with the data processing and the timing of the program. The achievable resolution is thereby mainly dependent upon the speed of the Analog/Digital converter (AD-converter) that is used. But also the time needed for application of the control voltage of the injector has to be considered. For the highest expected engine speed of 4000 rpm, and the used AD-converter, the minimum possible sampling rate is 0.2 °CA. This resolution is sufficient for the ILC, therefore it is fixed for all engine speeds.

The second dataset consisting of the pressure vector, is needed to calculate the indicated mean effective pressure of the high pressure phase

$$IMEP_{HP} = \frac{1}{V_h} \sum_{i=0}^{359} p(\Theta_i) \cdot \Delta V(\Theta_i) \quad (6)$$

to be able to operate the load governor. As load controller a Proportional-Integral governor (PI- governor) is used, whose control variable is the injection duration. For this task, a lower resolution is sufficient. The resolution can be reduced to 1 °CA to reduce the data processing load.

The breakdown of the engine strokes into the different data recording and calculation phases can be seen in figure 4.

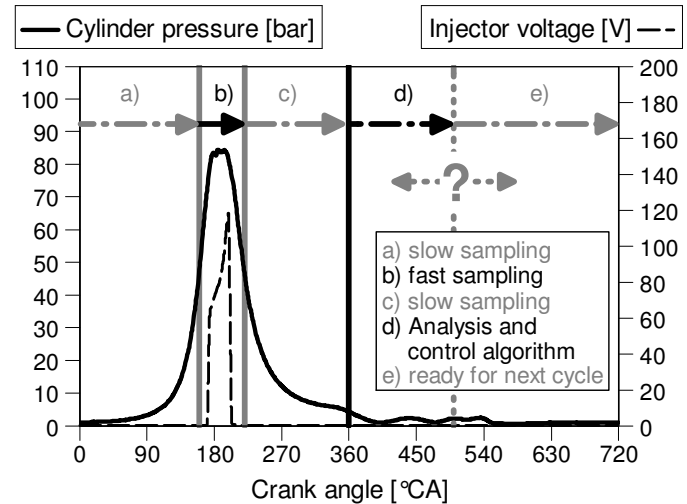


Figure 4: Phases of the data acquisition and processing of the realized indication system (slow sampling is at a rate of 1 °CA, fast sampling at 0.2 °CA)

Data recording during the low pressure phase is not used in the developed control system to gain additional calculation time for the control algorithm. Therefore the analysis and processing of the data starts right after the high pressure phase and is directly followed by the calculation of the control algorithm. The end of this calculation cannot be precisely predetermined; therefore it is marked with a question mark in figure 4. At this point, the control voltage profile for the next cycle is known. With an engine speed of 2280 rpm, the calculation is often finished at 440 °CA and therefore well before the end of the low pressure phase.

The voltage profile for the control of the injector is generated by the control system in three steps. In the first step a ramp is constructed depending on the pre-set start of injection, which ends when the voltage limit to “needle open” is exceeded. In the second part the voltage profile calculated by the ILC is used and limited between the minimum injection voltage (65 V) and the maximum injection voltage (120 V). The third part is determined by the load controller. In this part, the injection duration for the required load is adjusted and the closing ramp is constructed.

The injection profile will thereby not exceed the limits of the injector. This is checked at the end of each control cycle and corrected if necessary. The control voltage between the end of the switch-on ramp and start of the