

Cylinder Pressure Based Fuel Path Control for Non-Conventional Combustion Modes

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ABSTRACT

Model-based control strategies along with an adapted calibration process become more important in the overall vehicle development process. The main drivers for this development trend are increasing numbers of vehicle variants and more complex engine hardware, which is required to fulfill the more and more stringent emission legislation and fuel consumption norms. Upcoming fundamental changes in the homologation process with EU 6c, covering an extended range of different operational and ambient conditions, are suspected to intensify this trend.

One main reason for the increased calibration effort is the use of various complex aftertreatment technologies amongst different vehicle applications, requiring numerous combustion modes. The different combustion modes range from heating strategies for active Diesel Particulate Filter (DPF) regeneration or early SCR light-off and rich combustion modes to purge the NOx storage catalyst (NSC) up to partially premixed combustion modes. A combination of advanced physically oriented control strategies and new model-based calibration procedures seems therefore favorable in order to significantly reduce the overall calibration effort and increase the robustness for the different combustion modes.

Within this publication, a new model-based approach for fuel path control of Diesel engines is presented as an example of such an advanced control strategy. The control concept combines a model-based feed-forward control with a cylinder pressure based feedback control. The models for feed-forward control are derived by splitting the entire thermodynamic process into combustion and energy conversion. For feedback control new fuel path control parameters such as the "centroid-of-heat-release" are introduced and combined with a structure variable controller that changes the control parameters depending on the injection strategy. Besides a detailed description of the novel control algorithm, the benefits in terms of calibration effort are analyzed and discussed. Finally, for experimental validation the control strategy is implemented on a Rapid Control Prototyping (RCP) system. Exemplary results including a rich event during a transient acceleration are shown to illustrate the potential of the control concept.

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INTRODUCTION

Fuel path control in diesel engines has been so far widely limited to simple map based open loop control structures. The recent increase of the overall number of combustion modes with multiple torque producing injections [1] as well as the introduction of variable valve trains [2] make it more and more difficult to achieve the required control accuracy with reasonable calibration effort.

In order to substantially reduce the calibration effort more physically oriented control functions are required for future applications. In this context, also cylinder pressure based combustion control algorithms

[3, 4] are relevant key elements. They are on the one hand more accurate than the open loop algorithms and on the other hand also able to compensate many of the unavoidable disturbances acting on the fuel path. The control concept presented in this publication combines a model based feed forward control with a cylinder pressure based feedback control. The target of this new control concept is to simplify the calibration process for different combustion modes and to increase the overall robustness with respect to different operational and ambient conditions.

CONTROL CONCEPT

The control concept is based on an energy balance for the internal combustion engine. [Figure 1](#) shows the energy flow in a representative part load operating point of a passenger car Diesel engine.

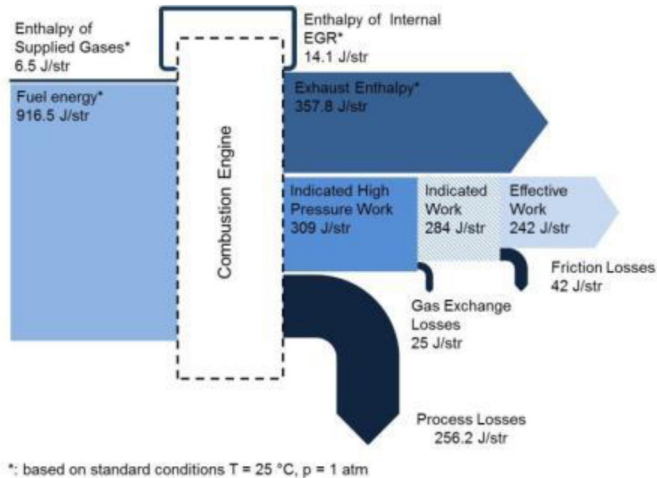


Figure 1. Energy flow (per cylinder and cycle) in a part load operating point, $n = 2000$ rpm, $b_{mep} = 6$ bar [1]

Inside the IC engine the heat supplied by the combustion of the fuel is converted into exhaust enthalpy, indicated high pressure work and additional process losses, which mainly consist of the heat transfer to the cooling medium and oil and the convection and radiation of the engine's external surfaces. The general task of a fuel path control concept is to determine the injection strategy, timings and quantities to achieve the desired effective work (torque at crankshaft) while considering exhaust emissions, combustion noise and additional combustion mode specific requirements. In the control concept presented in this paper this is achieved by modelling the energy conversion from injected fuel quantity to exhaust enthalpy and indicated high pressure work.

An overview of the structure of the control concept together with a schematic description of the process is given in [figure 2](#). The overall structure of the control algorithm remains the same for all possible combustion modes. In the first step, both, the desired combustion phasing ($\alpha_{Q, \text{Centroid}}$) and total fuel quantity (q_{total}), are calculated based on the above mentioned models of energy flow. The desired combustion phasing and total fuel quantity are subsequently used to determine the most suitable injection pattern (number of injections), while respecting the limits of the FIE system hardware. Finally, the fuel quantity is allocated to the different injections according to the desired combustion phasing and combustion timings by using a simplified combustion model. The different fuel injection quantities are then forwarded to an injector model to calculate the desired energizing time of each injection.

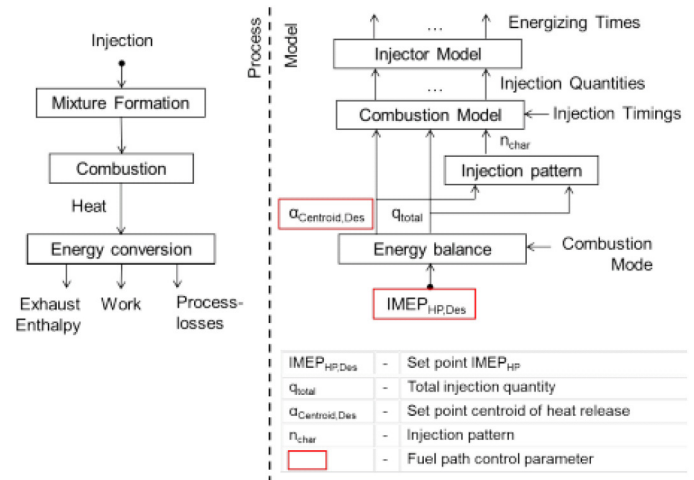


Figure 2. Schematic description of the process (left) and derived structure of the control concept (right)

The two set values in this control concept are the indicated mean effective pressure of the high pressure cycle ($IMEP_{HP}$) and the desired combustion phasing $\alpha_{Q, \text{Centroid}}$. The $IMEP_{HP}$ is obtained by adding the modelled friction and gas exchange losses to the effective torque request. For the combustion phasing a new parameter, the “centroid-of-heat-release”, first introduced in [5], is used, as opposed to the common approach to define the combustion phasing by the crank angle position of 50 % mass fraction burned. The “centroid-of-heat-release” is defined according to [equation 1](#), in which ϕ is the crank angle position and $dQ/d\phi$ is the rate of heat release.

$$\alpha_{Q,Centroid} = \frac{\int_{SOC}^{EOCdQ} \varphi \cdot d\varphi}{\int_{SOC}^{EOCdQ} d\varphi} \quad (I)$$

The “centroid-of-heat-release” corresponds to the center of the area underneath the heat release curve between start (SOC) and end of combustion (EOC) (see [figure 3](#)). As shown in [\[5\]](#) and [\[6\]](#) it is a reliable, valid and robust representation of the mean combustion phasing independent of the number of torque effective injections.

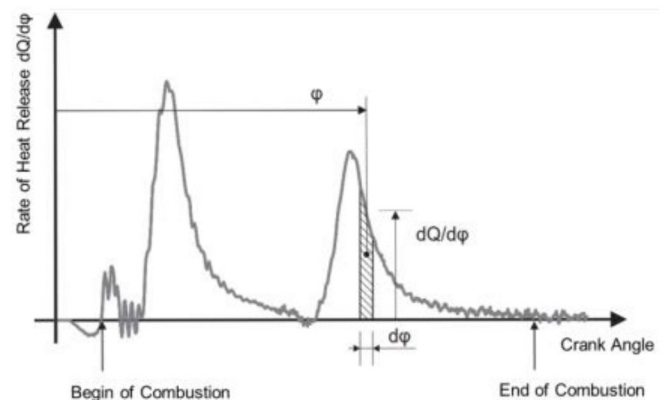


Figure 3. Definition of the centroid of heat release $\alpha_{O, \text{Centroid}}$

The subdivision of the model into an energy conversion and combustion part simplifies on the one hand the models and allows on the other hand a straightforward integration of a cylinder pressure based feedback control. The details of the different components of the control concept are explained in the following chapters.

Model Based Feed-Forward Control

The model based feed-forward control consists of the energy conversion and the combustion model (see [figure 2](#)). For each sub process dedicated models are derived.

The combustion process is simplified to a heat supply given by the energy of the injected fuel quantity and mean combustion phasing. For feed-forward control the combustion process needs to be described as a function of injection parameters. This is achieved by means of a simplified combustion model as shown in [figure 4](#).

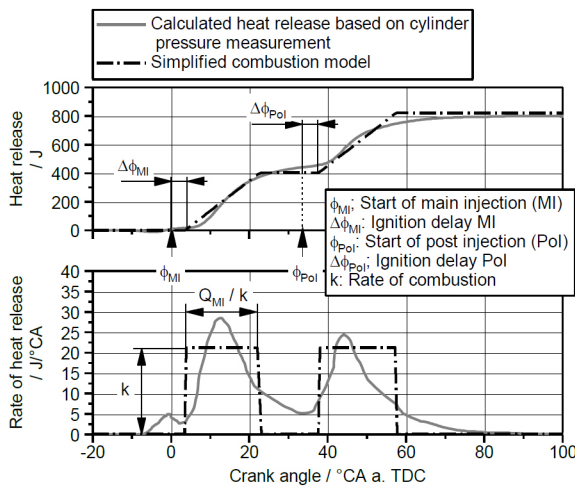


Figure 4. Simplified combustion model used to calculate the “centroid-of-heat-release based on the injection parameters

In this model the “centroid-of-heat-release” is approximated by the quantity weighted combustion phasing (α_c) of each injection (see [equation 2](#)), which is in turn modelled based on an engine operating point dependent ignition delay and rate of combustion (k).

$$\alpha_{Q, \text{Centroid}} = \frac{q_{MI}}{q_{\text{total}}} \cdot \alpha_{MI} + \frac{q_{Pol}}{q_{\text{total}}} \cdot \alpha_{Pol} + \dots \quad (2)$$

In the second sub process the energy conversion from heat supply to the target energy flow is modelled. The two energy flows that are considered in the feed-forward algorithm are the indicated high pressure work and the enthalpy difference (ΔH) between exhaust and intake gases. For modelling purposes the enthalpy difference is approximated by the cylinder charge m_{Cyl} multiplied with the specific heat capacity c_p and the temperature difference between exhaust T_3 and intake side T_2 :

$$\Delta H = m_{Cyl} \cdot c_p \cdot (T_3 - T_2) \quad (3)$$

The process losses are only implicitly modelled since they characterize no primary target for the fuel path control. Nonetheless the information about the process losses can be used for optimization of the overall thermal management.

The shares of the two target energy flows are described by two separate models. The share of the fuel's energy content which is converted into indicated high pressure work is given by the indicated high pressure efficiency ($\eta_{i,HP}$). Similarly, the share of the fuel's energy content which is converted into exhaust heat is captured by the specific difference of enthalpy (Δh), as depicted in [equation 4](#). In this equation q_{total} represents the total fuel quantity per cycle which is burned within the combustion chamber and LHV (the lower heating value of the fuel).

$$\Delta h = \frac{\Delta H}{q_{\text{total}} \cdot \text{LHV}} \quad (4)$$

The shares of both target energy flows are modelled as a function of the combustion phasing and air path boundary conditions using a black box model. The black box model is a second order Taylor series approach ([equation 5](#)) which has proven to be a suitable approximation of the energy flows that can easily be inverted for feed forward control.

$$y = y_0 + \sum_{i=1}^N \frac{\partial y}{\partial x_i} \cdot (x - x_{i,0}) + \frac{1}{2} \sum_{i=1}^N \frac{\partial^2 y}{\partial x_i^2} \cdot (x - x_{i,0})^2 \quad (5)$$

For each operating point the energy flow y is approximated as the sum of a base value y_0 and the partial first and second order derivatives of all relevant influencing variables x_i . The partial second and first order derivatives are obtained using a design of experiments (DoE) approach in which all relevant influencing variables, such as e.g. combustion phasing, intake manifold temperature, are varied.

For feed-forward control the models of the energy and combustion are combined and inverted in order to calculate the desired combustion phasing and total fuel quantity. As the targets of the different combustion modes vary, different algorithms need to be created. For this purpose the combustion modes are clustered into three target modes:

1. Efficiency target mode
2. Exhaust temperature target mode
3. Air-fuel-ratio (λ) target mode

In all target modes the primary target is the achievement/maintenance of the desired load (IMEP_{HP}). The secondary target differs. [Figure 5](#) lists different combustion modes and shows their assignment to the target modes defined above.