A dynamic PCCI combustion model for Diesel engine control design

C. Felsch[1*], K. Hoffmann[2], A. Vanegas[1], P. Drews[2], T. Albin[2], D. Abel[2], N. Peters[1]
[1]Institut für Technische Verbrennung
RWTH Aachen University, Aachen, Germany
[2]Institut für Regelungstechnik
RWTH Aachen University, Aachen, Germany

Subject of this work is a dynamic simulation model for PCCI combustion that can be used in closed-loop control development. A detailed multi-zone chemistry model for the high-pressure part of the engine cycle is extended by a mean value model accounting for the gas exchange losses. The resulting model is capable of describing PCCI combustion with stationary exactness. It is at the same time very economic with respect to computational costs. The model is further extended by identified system dynamics influencing the stationary inputs. For this, a Wiener model is set up that uses the stationary model as a nonlinear system representation. In this way, a dynamic nonlinear model for the representation of the controlled plant Diesel engine is created. This paper summarizes the work already described in [Hoffmann et al., A Cycle-Based Multi-Zone Simulation Approach Including Cycle-to-Cycle Dynamics for the Development of a Controller for PCCI Combustion, SAE paper 2009-01-0671, 2009] and [Felsch et al., Combustion model reduction for Diesel engine control design, Int. Journal of Engine Research, 2009, submitted].

Introduction

In the recent past, several efforts have been reported in the literature that aim at controlling engine combustion. The standard procedure for creating a controller includes the modeling part as the first step. Often this model differs in several aspects from models widely used for gathering a deeper understanding of combustion details, like three-dimensional computational fluid dynamics (CFD) models. From the viewpoint of automatic control, the dynamics describing the dependency of the system's outputs/controlled variables (IMEP, CA50) on the actors (SOI, external EGR rate, and total fuel mass injected) is of highest priority. Nevertheless, stationary exactness of the model is important, too. Another requirement is an acceptable calculation speed, as it is often applied in dynamic closed-loop simulations.

This paper presents a new approach to the development of a simulation model for the use in closed-loop control development. The model is based on a recently introduced multi-zone model for PCCI combustion that was derived from a detailed CFD approach. It covers the nonlinear dependencies within the high-pressure part of the engine cycle with stationary exactness. This model is extended by a physically inspired description of the gas exchange part of the engine cycle. For the use in closed-loop simulations, the system's dynamics have to be covered. For this reason, the stationary model is further extended by identified system dynamics influencing the stationary inputs. In this manner, a stationary exact model is extended to a Wiener-type model with a static part describing the nonlinearities and an upstream part describing the system's dynamics. This novel proceeding integrates the detailed knowledge from combustion simulation tools into closed-loop control and establishes a broad field of possibilities for testing completely new controlled process variables.

Combustion Model Formulation

Crucial for reacting turbulent flows is the modeling of the chemistry. Here, a multi-zone chemistry model is employed. It covers the nonlinear dependencies within the high-pressure part of the engine cycle with stationary exactness.

The multi-zone model employed in the current study is X0D, a zero-dimensional chemistry solver based on multiple zero-dimensional reactors. X0D was developed internally at General Motors R&D by Hardo Barths, Tom Sloane, and Christian Hasse, and was first described in Hergart et al. [1]. The governing equations account for species mass fraction conservation, temperature, and pressure change in each zone. The multi-zone model also includes mass exchange between zones, wall heat transfer, as well as fuel injection and vaporization. The underlying chemical mechanism comprises 59 elementary reactions among 38 chemical species. This mechanism mainly describes low-temperature auto-ignition and combustion of n-heptane, which serves as a surrogate fuel for Diesel in this work. Further details are given in [2].

Stationary Validation

At the Institut für Technische Verbrennung at RWTH Aachen University, Germany, experiments were carried out with a 1.9l GM Fiat Diesel engine. This engine is equipped with a second-generation Bosch Common-Rail injection system and an EDC16 electronic control unit. A more detailed description regarding the engine, the test cell equipment, and injection rate measurements can be found in Vanegas et al. [3].

The engine was operated at part-load conditions with a speed of 2000 rpm. For this study, 50 different stationary experiments were carried out

* Corresponding author: c.felsch@itv.rwth-aachen.de

with variations in external EGR rate, start of injection (SOI), and total fuel mass injected (FMI).

Figure 1 shows the achieved modeling results in terms of pressure curve, indicated mean effective pressure of the high-pressure cycle ($IMEP_{HP}$), and crank angle of 50% burnt fuel mass (CA50) in comparison to test bench measurements for five selected operating conditions TS-1 through TS-5. There is a very good qualitative and quantitative agreement.

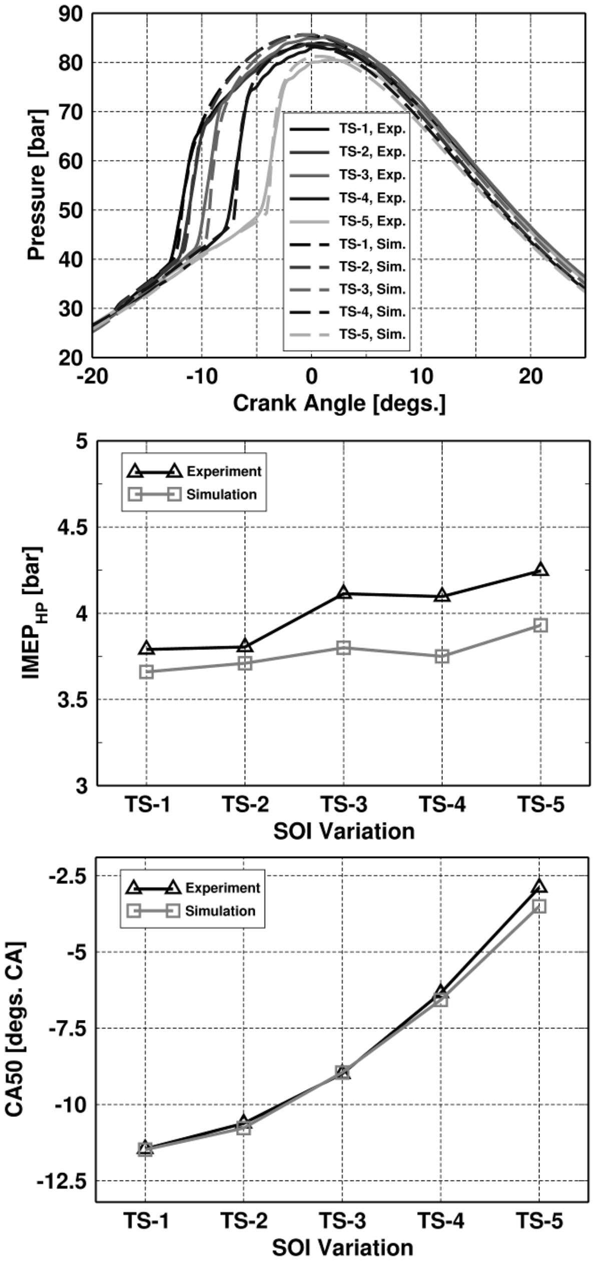

Fig. 1: Average cylinder pressure (top), $IMEP_{HP}$ (center), and CA50 (bottom) for five selected operating conditions TS-1 through TS-5. Comparison between simulation and experiment

Gas Exchange Modeling

The stationary validation described in the previous section is restricted to the high-pressure part of the engine cycle. The usage of the multi-zone model within a closed-loop controller for PCCI combustion requires that it is capable of predicting the dependency of the controlled variables on the actuators. As mentioned in the “Introduction”, the actuators are SOI, external EGR rate, and FMI. The controlled variables are the IMEP and CA50. The latter is directly obtained from a simulation with the multi-zone model. The former, however, can only be predicted for the time frame from closing of the intake until opening of the exhaust valves. For this reason, the calculation of the $IMEP_{HP}$ is extended to the gas exchange part of the engine cycle.

The calculation of the indicated mean effective pressure throughout the gas exchange ($IMEP_{GE}$) is physically inspired by pumping losses. This approach is further explained in [4]. After an appropriate fitting, the approach is capable of predicting the $IMEP_{GE}$ within 5% accuracy for most of the 50 operating conditions mentioned above (see Fig. 2).

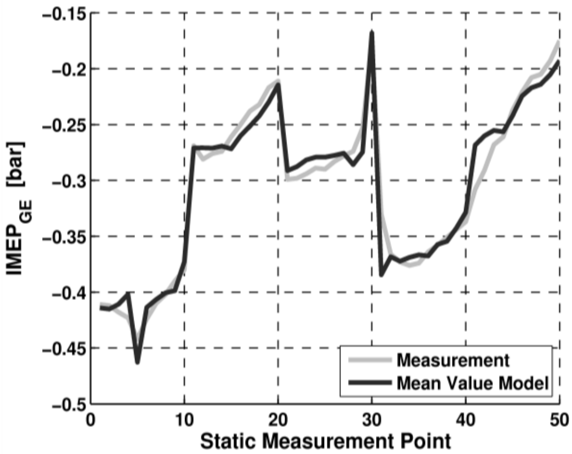

Fig. 2: $IMEP_{GE}$ of the gas exchange for all 50 experiments mentioned above. Comparison between mean value model calculation and experiment

Combining the multi-zone model X0D with this gas exchange model therefore leads to a static model, which can be used to determine the static dependency of the controlled variables IMEP and CA50 on the actuated variables SOI, external EGR rate, and FMI.

System Identification

The combination of multi-zone model and mean value model for the $IMEP_{GE}$ does so far not include any dynamics of the controlled variables. Hence, a structure was chosen, which is suitable for adding the dynamic aspect to the static accurate model. As the dynamic physical behaviour of the real engine shall be enforced on the whole static model, a Wiener-type dynamics was implemented. With this choice, the inputs to the static model are overlaid with time attributes, which enforces the dynamic behaviour on the combustion simulation. Thus, IMEP and CA50 are consequently affected by the identified dynamics.

For identifying the system's dynamics or the system's dynamic transfer functions, respectively, various step response experiments were carried out. These are described in detail in [4].

Integrated Model

For application within a closed-loop control simulation, the multi-zone model was transferred to an environment suitable for the conception and testing of controllers. The multi-zone model X0D written in FORTRAN 77 was embedded into a Matlab/Simulink FORTRAN s-function enabling the simulation of the multi-zone model from within Matlab/Simulink. Moreover, the gas exchange model was implemented into this s-function. The three identified dynamic transfer functions were added by means of time-discrete PT_1-dynamics within appropriate function blocks.

Figure 3 shows IMEP and CA50 obtained from the step response experiment, the system identification with the corresponding identified discrete transfer function, and the transient simulation with the integrated model for an SOI step from -20.7 to -30.7 °CA aTDC and back with an external EGR rate of 30% and an injected fuel mass of 10.2 mg/cycle. The simulation results are in very good agreement with the measurements. In particular, the dynamic step responses are reproduced well. Additional results may be found in [2]. This validates the integrated model composed of the multi-zone model, the gas exchange model, and the identified system dynamics.

Summary and Conclusions

Closed-loop simulations are a necessary and common tool in the development process of controllers. A computationally efficient multi-zone model was employed that is capable of describing the combustion characteristics for the high-pressure part of the engine cycle. The controller to be developed shall actuate SOI, external EGR rate, and total fuel mass injected to control the IMEP of the whole engine cycle and the CA50. The $IMEP_{HP}$ of the high-pressure engine cycle and the CA50 can be extracted from simulations with the multi-zone model. The former was combined with a mean value model for the losses of the gas exchange to calculate the IMEP of the whole engine cycle. The combination of these models leads to an accurate static model, which was further extended to a Wiener model for capturing temporal cycle-to-cycle dependencies. For every input of the model, a transfer function was determined, forcing the whole model to follow the engine's dynamics. All model parts (multi-zone model, mean value model for the gas exchange, and dynamic time response) were each validated separately. Afterwards, the integrated model composed of all three model parts was validated against transient experimental data.

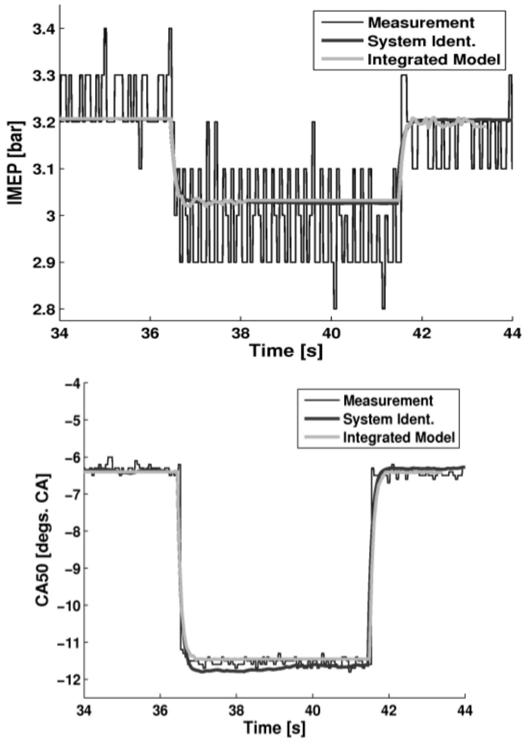

Fig. 3: IMEP (top) and CA50 (bottom) for an SOI step from -20.7 to -30.7 °CA aTDC and back with an external EGR rate of 30% and an injected fuel mass of 10.2 mg/cycle. Comparison between experiment, system identification, and integrated model

Acknowledgment

This work was funded within the collaborative research center "SFB 686 - Modellbasierte Regelung der homogenisierten Niedertemperatur-Verbrennung" at RWTH Aachen University, Germany, and Bielefeld University, Germany [5].

References

[1] C.-A. Hergart, H. Barths, R.M. Siewert, Modeling Approaches for Partially Premixed Compression Ignition Combustion, SAE paper 2005-01-0218, (2005).

[2] C. Felsch, K. Hoffmann, A.Vanegas, P. Drews, H. Barths, D. Abel, N. Peters, Combustion model reduction for Diesel engine control design, Int. Journal of Engine Research, (2009), submitted.

[3] A. Vanegas, H. Won, C. Felsch, M. Gauding, N. Peters, Experimental Investigation of the Effect of Multiple Injections on Pollutant Formation in a Common-Rail DI Diesel Engine, SAE paper 2008-01-1191, (2008).

[4] K. Hoffmann, P. Drews, D. Abel, C. Felsch, A. Vanegas, N. Peters, A Cycle-Based Multi-Zone Simulation Approach Including Cycle-to-Cycle Dynamics for the Development of a Controller for PCCI Combustion, SAE paper 2009-01-0671, (2009).

[5] RWTH Aachen University and Bielefeld University, SFB 686 - Modellbasierte Regelung der homogenisierten Niedertemperatur-Verbrennung, *http://www.sfb686.rwth-aachen.de*.