Chapter 6
Modeling and Model-based Control of Homogeneous Charge Compression Ignition (HCCI) Engine Dynamics

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Abstract. The Homogeneous Charge Compression Ignition (HCCI) principle holds promise to increase efficiency and to reduce emissions from internal combustion engines. As HCCI combustion lacks direct ignition timing control and auto-ignition depends on the operating condition, control of auto-ignition is necessary. Since auto-ignition of a homogeneous mixture is very sensitive to operating conditions, a fast combustion phasing control is necessary for reliable operation. To this purpose, HCCI modeling and model-based control with experimental validation were studied. A six-cylinder heavy-duty HCCI engine was controlled on a cycle-to-cycle basis in real time using a variety of sensors, actuators and control structures for control of the HCCI combustion in comparison. The controllers were based on linearizations of a previously presented physical, nonlinear, model of HCCI including cylinder wall temperature dynamics. The control signals were the inlet air temperature and the inlet valve closing. A system for fast thermal management was installed and controlled using mid-ranging control. The resulting control performance was experimentally evaluated in terms of response time and steady-state output variance. For a given operating point, a comparable decrease in steady-state output variance was obtained either by introducing a disturbance model or by changing linearization point. Additionally, the robustness towards disturbances was investigated.

6.1 Introduction

The motivation for studying the homogeneous charge compression ignition (HCCI) engine principle is the promise of low levels of exhaust emissions with regards to
NO\textsubscript{x}, while still retaining an acceptable overall efficiency [17]. Pioneering efforts towards this new engine principle, also called controlled auto-ignition (CAI), were reported in [16, 23, 32, 43, 58]. Depending on the purpose, modeling of HCCI engine dynamics may exhibit different complexity and format such as:

- multi-zone models including chemical kinetics to simulate engine operation in a large operating range;
- multidimensional CFD for optimization of fuel injection and combustion chamber design; and
- single-zone reduced-order dynamic models (for model-based control).

A significant challenge with HCCI is the control of the combustion phasing, this is essential in order to control the load, to obtain low fuel consumption and emissions. For closed-loop control of the combustion phasing, feedback signals are necessary and in-cylinder pressure feedback is, perhaps, the most straightforward approach. In practice, the crank angle \(\alpha\) of 50\% burnt fuel (CA50 or \(\alpha_{50}\) or \(\theta_{50}\)) has proved to be a reliable indicator of on-going combustion [6, 42]. In closed-loop control of an HCCI engine, several means to actuate the combustion phasing have been tested – e.g., dual fuels [42], variable valve actuation (VVA) [1, 8], variable compression ratio [17, 29], and thermal management [30, 39].

For control design purposes appropriate models and system variables useful for feedback control are needed. Previously, it was shown that physical modeling and system identification can be used to obtain low-complexity models of the HCCI dynamics [52, 7, 52]. For closed-loop HCCI engine operation, it was reported that the combustion phasing can be stabilized by means of a PID controller [42]; LQG control [59]; and MPC control [8].

A fast and robust control of \(\alpha_{50}\) appears to be necessary in order to stabilize HCCI engine control. It is also desirable that the load, peak cylinder pressure, peak rate of cylinder pressure and emissions are controlled simultaneously. This is a multi-input multi-output (MIMO) control problem where the controller has to be able to handle constraints on several variables. In a comparison among several control methods, it will be demonstrated that Model Predictive Control (MPC) control could be used with favorable properties [4, 36]. All of the actuators suggested have control constraints and MPC has the benefit of explicitly taking the constraints into account.

Whereas monitoring of \(\alpha_{50}\) or other methods to sense on-going combustion for feedback control of an HCCI engine all rely on pressure sensors, these sensors may be expensive. One candidate to replace pressure sensors is the use of electronic conductive properties for the reaction zone [26]. This phenomenon is called ion current for which no expensive sensor is needed. Ion current has been successfully used in closed-loop control of SI engines [22]. The basic principle of ion current sensing is that a voltage is applied over an electrode gap inserted into the gas volume (combustion chamber) [26]. The common belief so far has been that ion current levels are not measurable for the highly diluted HCCI combustion. However, a recent study shows that it is not the dilution level in itself but the actual fuel/air equivalence ratio \(\phi\) which is an important factor for the signal level [24, 59].