Chapter 17
Optimal Control of HCCI

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Abstract HCCI (Homogeneous Charge Compression Ignition) is a very control-intensive combustion concept which has been studied for over a decade because of its favorable combination of high efficiency and low emissions. Various optimal control methods have been applied to HCCI and this chapter gives an overview of them. Optimal control of HCCI can be divided into model based and non-model based where MPC is an example of model based and extremum seeking control is an example of non-model based control. The model-based methods can be divided based on whether they use physics based or black box models. Finally a division can be made based on whether the control aims for optimal set-point tracking of e.g. combustion timing or whether it attempts to optimize an overall design criterion such as fuel consumption. This chapter presents and characterizes a number of published methods for optimal HCCI control and characterizes them according to the above criteria.

17.1 Introduction

HCCI (Homogeneous Charge Compression Ignition) combustion has been studied intensely for more than a decade because of its ability to combine high efficiency with low emissions of particularly nitric oxides (NOx) and soot. One great difficulty with HCCI is however, that it lacks direct control of ignition. Unlike spark ignition combustion which is ignited by a spark and diesel combustion where ignition is triggered by fuel injection, HCCI combustion has spontaneous ignition of a homogeneous charge which means that the charge conditions have to be very accurately controlled in order to assure ignition at the right time.

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The problem with controlling HCCI combustion timing has been recognized by many researchers [1, 2] and many different control methods have been devised. A majority of the published solutions have applied linear control e.g. PID [3] or linear state feedback [4] with simple, low-level, control objectives such as tracking a desired combustion timing trajectory. The main merits with these linear control methods are low complexity, robustness and tunability.

Perfect tracking of combustion timing is however, not interesting in itself but rather a tool to achieve other goals. Such goals could be low fuel consumption and/or low emissions. This is recognized by some of the optimal control methods where the optimality criterion is specified directly in terms of e.g. fuel consumption. Another shortcoming of the linear control methods is constraint handling. Constraints are nonlinear artifacts and as such can not be handled by truly linear controllers. For this reason special constraint handling is added e.g. integrator windup protection, often with less than satisfactory results.

Constraint handling is thus another reason to apply optimal control methods such as MPC (model predictive control) which is essentially online constrained optimization. With MPC the constraints can be explicitly taken into account in the optimization and thus there is no need to add separate constraint handling. This chapter presents examples of extremum seeking control as well as MPC control to illuminate the issues mentioned above.

17.2 Optimal Control of HCCI

17.2.1 Multi-output MPC of HCCI

In [4], Bengtsson et al. show the first example of MPC (Model Predictive Control) applied to control of HCCI combustion. The modeling approach is system identification of cylinder individual MIMO models using the subspace identification method. Excitation was provided by individually designed PRBS (Pseudo-Random Binary Sequence) signals on each input.

The test engine had a dual-fuel port injection system capable of injecting individual quantities of ethanol and n-heptane to each cylinder. It also had a cylinder-individual VVT (variable valve timing) system capable of changing the (IVC) intake valve closing angle from cycle to cycle which was not used in this control implementation.

The input/output selections for the HCCI cylinder models are illustrated in Fig. 17.1. The inputs selected for the cylinder models were fuel mass per cycle (W_f), fraction of ethanol (R_f), inlet temperature (T_i) and engine speed (n). The outputs were combustion timing (α_{50}), load ($IMEP_n$) and maximum pressure derivative ($dp/d\theta$). $dp/d\theta$ represents the combustion noise and a reasonable limit for the heavy duty test engine in the study is 15 bar/CAD (crank angle degree).

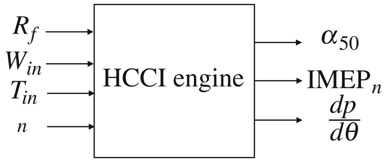

Fig. 17.1 The multi-input/multi-output HCCI engine cylinder model used for multi-output MPC control design [4]

The MPC design took a fairly simplistic approach where α_{50} was kept as close to TDC (top dead center) as possible in order to minimize HC (hydrocarbon) and CO (carbon monoxide) emissions. The tracking error of $IMEP_n$ was also included in the cost function. Hard constraints were applied on inputs and soft constraints on outputs, most importantly $dp/d\theta$ which was given a soft constraint of 15 bar/CAD.

Figure 17.2 shows an experiment where multiple stepwise load changes are applied. It can be seen that α_{50} is delayed when necessary to satisfy the constraint. When it is impossible to delay α_{50} further the $IMEP_n$ tracking is sacrificed by reducing the fuel mass.

17.2.1.1 Discussion

The strength of this approach is that it can minimize a cost function subject to multiple constraints which can be both simple input saturation constraints and output constraints. In this example the cost function was very simple. A more complicated cost function would have made the optimization problem more complex and the computation time would have increased substantially.

17.2.2 Physics-Based MPC of HCCI Combustion Timing

In [6] Widd et al. takes a physics based approach to MPC control of HCCI combustion. A central part is a sub-model describing the heat transfer between cylinder gas, cylinder walls and engine coolant. The continuous heat transfer is modeled as taking place at three specific time instances in each cycle: after intake/mixing, after combustion and after the exhaust stroke. The heat transfer model is illustrated in Fig. 17.3. The individual durations of the heat transfer events were tuning parameters.

Ignition was modeled using a simplified Arrhenius rate threshold model were the temperature was approximated by the TDC temperature. Compression and expansion were modeled as isentropic processes and $IMEP_n$ could be derived from cycle temperatures using ideal cycle analysis.

The inputs to the model were the inlet valve closing angle (θ_{IVC}) and T_i and the outputs were $IMEP_n$ and combustion timing (θ_{50}). The resulting model is of second order and a linearization was used for the MPC design. The control objective was θ_{50} tracking but a small weight was introduced on $\theta^r_{IVC} - \theta_{IVC}$, where θ^r_{IVC} is a reference

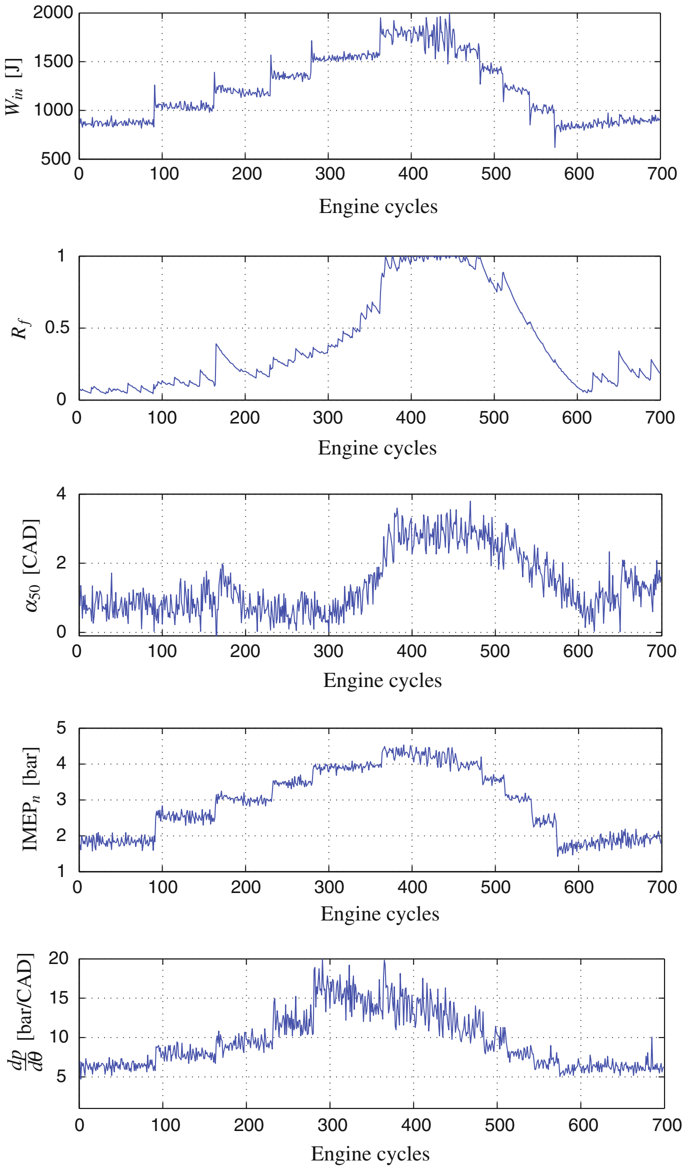

Fig. 17.2 Multiple load step changes illustrating the characteristics of the multi-output MPC controller [5]

crank angle in the middle of the controllable range of the inlet valve closing angle, in order to achieve a midranging [7] effect since T_i and θ_{IVC} are to some extent redundant. Midranging is a heuristic control design method that can be used when two control inputs affect the same output. If one of the control inputs has a high

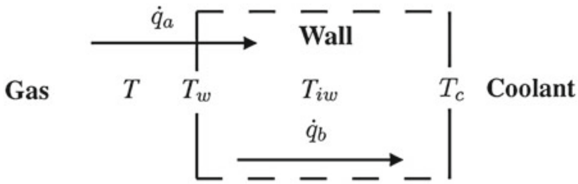

Fig. 17.3 Illustration of the heat transfer model used for physics based MPC control of HCCI combustion [6]

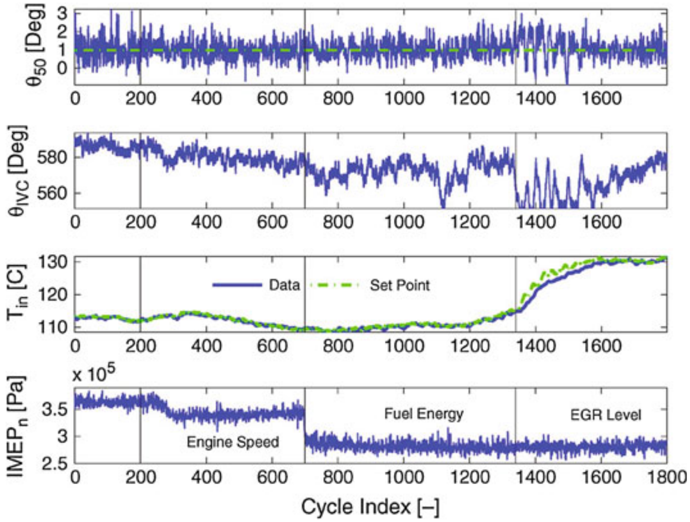

Fig. 17.4 Illustration of the disturbance rejecting characteristics of the physics-based MPC controller with respect to disturbances in engine speed, fuel enginery and EGR level [6]

bandwidth and the other one has a wide range, the slow control input can be used to push the fast one towards the middle of its range and thus make sure that high bandwidth control is always possible.

Due to the low model order short prediction and control horizons could be used which kept the computational load at a reasonable level. Figure 17.4 shows a disturbance rejection experiment with the physics based MPC controller which is able to reject disturbances in engine speed, fuel mass and EGR level.

17.2.2.1 Discussion

The physics-based approach to MPC is attractive since it provides modularity and a component-based structure. E.g. if material of the cylinder liner is changed in the presented example, only the heat-transfer part of the entire model is affected and everything else stays the same. For an identified black-box model, the entire identification would have to be repeated with the new hardware.

In this example the inlet valve closing timing and the inlet temperature are somewhat redundant in controlling the combustion phasing and then a midranging functionality can be obtained by adding a weak penalty to deviations in the intake valve closing timing from a reference value in the middle of its range, thus assuring maneuverability at all times.

17.2.3 Hybrid MPC of Exhaust Recompression HCCI

In [8] Widd et al. take a similar physics based modeling approach is in [6] but without the heat transfer model. The reason for omitting the heat transfer is that the engine used in this case operates with exhaust recompression with a considerable amount of burned gas retained from one cycle to the next. The heat transfer then has a minor influence on the charge temperature and instead focus is on the effect of NVO (negative valve overlap). NVO is the crank angle interval when both exhaust valves and inlet valves are closed around gas exchange TDC. By varying the NVO, the amount of retained burned gas and thus the charge temperature can be controlled. As in [6], the model is of second order. In [8] it is noted that the combustion timing behavior is quite different for early and late combustion timings respectively (see Fig. 17.5) with more cycle-cycle variation and less damping in the case of late combustion. For this reason different linearizations are used for early, mid and late combustion timings respectively in order to improve the control performance.

Tracking control of θ_{50} is implemented both using switching LQ design and using hybrid MPC and a comparison for a large setpoint change is shown in Fig. 17.6. It can be seen that the hybrid MPC controller handles the setpoint change significantly better and the reason is believed to be the fact that the hybrid MPC controller can anticipate the system behavior by using the correct linearization when jumping between early, mid and late combustion timing. The LQ controller can however, only use one linearization at a time based on the present combustion timing.

17.2.3.1 Discussion

The hybrid MPC is suitable for cases when the operating range can be partitioned into a small number of regions with similar system behavior within each region. The MPC can then perform nearly optimally throughout the operating range and even during transitions between regions. It can still be used for systems where the necessary number of regions is larger but the memory requirement as well as the identification effort will scale with the number of regions.

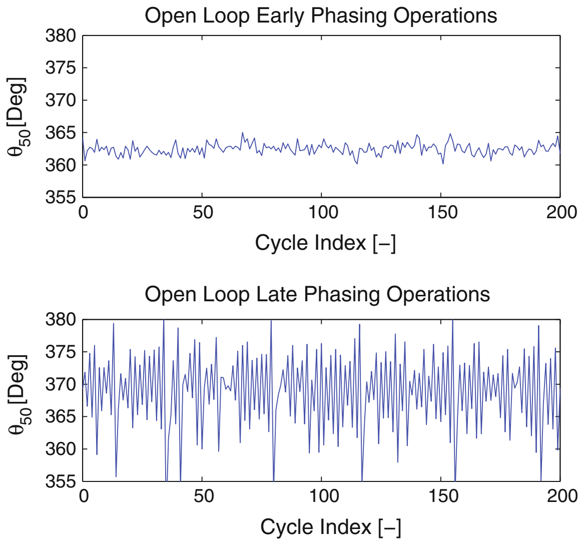

Fig. 17.5 Combustion timing behavior at early and late combustion timing respectively [8]

17.2.4 Optimizing Gains and Fuel Consumption of HCCI Using Extremum Seeking

In [9] a completely non-model based approach is taken where extremum seeking control is used for both tuning of controller gains for combustion timing control and subsequently for fuel consumption minimization by optimizing the combustion timing. The extremum seeking control is defined in Fig. 17.7 and minimizes the cost function $J(\theta)$ with respect to the parameter θ.

Extremum seeking calibration of the control parameters is achieved by defining the cost function as the tracking error and performing repeated positive and negative step changes of the combustion timing (CA50) setpoint. Figure 17.8 illustrates how PI parameters and a feed forward gain are optimized in 1600 s using this approach.

Using the calibrated CA50 controller extremum seeking control of CA50 was subsequently applied in order to minimize fuel consumption. Figure 17.9 shows how the fuel-optimal CA50 is found in approximately 2,000 s.

17.2.4.1 Discussion

Extremum seeking is attractive since it does not require a system model. It can also handle any type of cost function without local optima. The drawbacks with extremum seeking is that it usually requires artificial excitation and the excitation normally has to be of significantly lower frequency than the bandwidth of the system. Each

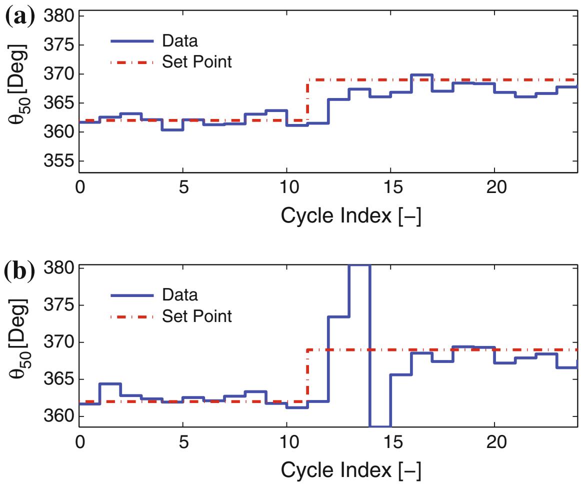

Fig. 17.6 Comparison of large setpoint changes for MPC and LQ controllers [6]

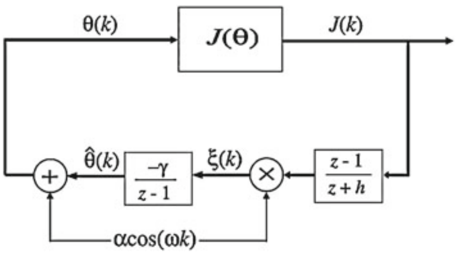

Fig. 17.7 Discrete extremum seeking control with sinusoidal excitation and optimization of the cost function $J(\theta)$ [9]

additional parameter to be optimized requires its own excitation frequency which means slower convergence.

17.3 Conclusions

Four different optimal HCCI control methods have been presented of which three are based on MPC. MPC is valuable for HCCI control mainly because of its ability to explicitly handle constraints. MPC can be applied both to black-box models based on system identification and to linearized physics-based models. When using piece-wise linear models MPC can anticipate model switching which can greatly improve the dynamic behavior for e.g. large setpoint changes. Second order models and relatively short prediction and control horizons have been sufficient for the presented cases and thus the resulting MPC designs have reasonable computational demands. Extremum

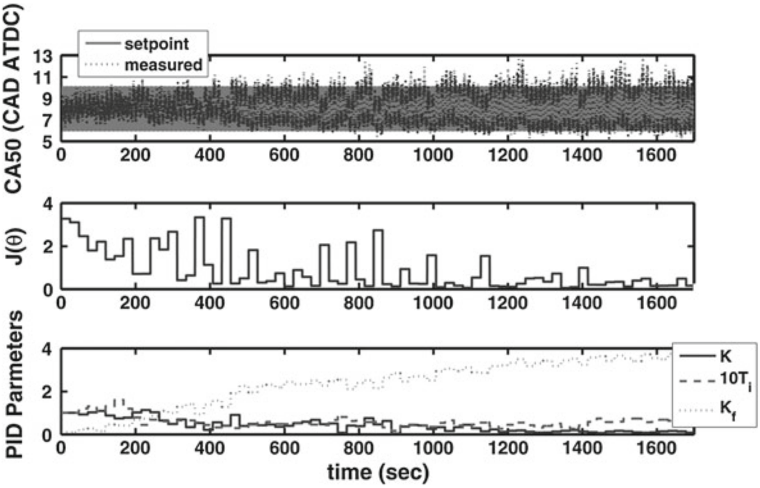

Fig. 17.8 Extremum seeking calibration of PI and feedforward gains [9]

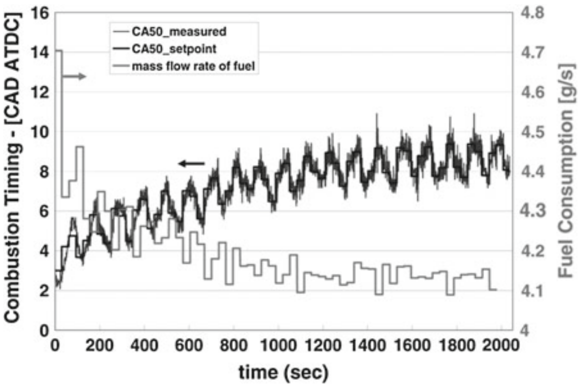

Fig. 17.9 Fuel consumption minimization using extremum seeking control of combustion timing [7]

seeking control provides a completely non-model based alternative. The advantage compared to MPC is that there is no need to derive and calibrate models but extremum seeking is essentially to be considered as a steady-state calibration method since the closed-loop bandwidth is a few orders of magnitude lower than for the presented MPC methods.

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