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Transient Control of Combustion Phasing and Lambda in a 6-Cylinder Port-Injected Natural-gas Engine

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ABSTRACT

Fuel economy and emissions are the two central parameters in heavy duty engines. High EGR rates combined with turbocharging has been identified as a promising way to increase the maximum load and efficiency of heavy duty spark ignition engines. With stoichiometric conditions a three way catalyst can be used which keeps the regulated emissions at very low levels. The Lambda window which results in very low emissions is very narrow. This issue is more complex with transient operation resulting in losing brake efficiency and also catalyst converting efficiency.

This paper presents different control strategies to maximize the reliability for maintaining efficiency and emissions levels under transient conditions. Different controllers are developed and tested successfully on a heavy duty 6-cylinder port injected natural gas engine. Model Predictive Control (MPC) was used to control lambda which was modeled using System Identification. Furthermore, a Proportional Integral (PI) regulator combined with a feedforward map for obtaining Maximum Brake Torque (MBT) timing was applied. The results show that excellent steady-state and transient performance can be achieved.

INTRODUCTION

Recently, environmental improvement and energy issues have become increasingly important as worldwide concerns. Road transport is one of the biggest energy consuming sectors which have a great impact on the environment. The fuels mainly used in internal combustion engines are petroleum products namely gasoline and diesel. One way for reducing these impacts is to use alternative fuels. Natural gas consisting mainly of methane (~90%) is a good alternative fuel to improve environmental problems because of its plentiful availability and clean burning characteristics.

Heavy duty spark ignited (SI) natural gas engines can be operated either lean or stoichiometric. Recent work at the department of energy sciences at Lund University has shown better results with stoichiometric operation [1] since stoichiometric operation with a three way catalyst results in very low emissions while keeping efficiency at a reasonable level. A reliable and sophisticated control strategy is essential for achieving good catalyst efficiency and hence low emissions. Accurate stationary and transient lambda control is very important for maintaining good catalyst efficiency and consequently low emissions.

A lot of research on controlling lambda and Air/Fuel Ratio (AFR) has been performed; some of it is reported in [2-4]. Model Predictive Control (MPC) is a model based control strategy that uses prediction to optimize future control actions with respect to a cost function [5]. The optimization cost function is given by:

$$J = \sum w_{x_i} (r_i - x_i)^2 + \sum w_{u_i} \Delta u_i^2$$

where x_i is the control variable, r_i the reference variable, u_i the manipulated variable and w is a weighting coefficient. The main reasons for applying MPC control are its capability to handle multivariable control problems and account for actuator constraints. Use of MPC for controlling lambda has not been reported previously.

The objective of this work is to develop a MPC controller to control the overall AFR. For being able To use MPC a model is needed for capturing the dynamics between fuel injection, throttle position and measured lambda. System identification tools were used for modeling. Furthermore a Maximum Brake Torque (MBT) Timing control was developed for increasing the reliability of ignition timing during transient operation.

EXPERIMENTAL SETUP

In this section the specification of the experimental engine and its control system, the measurement system and gas data are described.

THE ENGINE

The experimental engine was originally a diesel engine from Volvo which has been converted to a natural gas engine, see Table 1 for specification. The engine is equipped with a short route cooled EGR system and also turbocharger with wastegate.

Number of Cylinder	6
Displacement	9,4 Liter
Bore	120 mm
Stroke	138 mm
Compression ratio	10,5 :1
Fuel	Natural gas

Table 1: Specification of the engine

Originally the engine has single point injection system which is replaced by a multi-port injection system. The main idea with this modification is to control the fuel injection of each cylinder individually and also to get rapid engine response to change throttle position.

ENGINE CONTROL SYSTEM

A master PC based on GNU/Linux operating system is used as a control system. It communicates with three Cylinder-Control-Modules (CCM) for cylinder-individual control of ignition and fuel injection via Controller Area Network (CAN) communication, see Figure 1. Crank and cam information are used to synchronize the CCMs with the crank rotation.

Flexible controller implementation is achieved using Simulink and C-code is generated using the automatic code generation tool of Real Time Workshop. The C-code is then compiled to an executable program which communicates with the main control program. The controllers used for this experiment are lambda, load and EGR controller which determine the offset amount of fuel, air and EGR. The controllers can be activated from the Graphical User Interface (GUI).

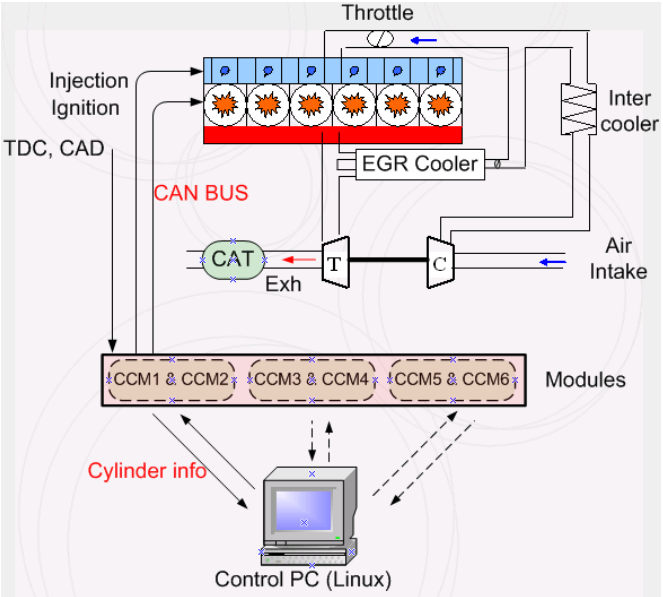

Figure 1: The Engine and its control system

MEASUREMENT SYSTEM

Each cylinder head is equipped with a piezo electric pressure transducer of type Kistler 7061B to monitor cylinder pressures for heat release calculations. Cylinder pressure and ion-current data are sampled by a Microstar 5400A data acquisition processor. EGR was calculated by measuring CO_2 at inlet and exhaust. Emissions (HC, CO, NO, NO_2, NO_x, CO_2, O_2) are measured before and after catalyst. Also, temperatures at inlet/exhaust, pressures at inlet/exhaust, fuel and air flow, lambda, torque and engine speed are measured.

GAS DATA

The composition of the natural gas, which varies slightly over time, is shown in Table 2. The lower heating value is 48,4 MJ/kg.

Composition	%	Structure
Methane	89,84	CH_4
Ethane	5,82	C_2H_6
Propane	2,33	C_3H_8
I-Butane	0,38	C_4H_{10}
N-Butane	0,52	C_4H_{10}
I-Pentane	0,11	C_5H_{12}
N-Pentane	0,07	C_5H_{12}
Hexane	0,05	C_6H_{14}
Nitrogen	0,27	N_2
CO2	0,6	CO_2

Table 2: The natural gas composition

CONTROL APPROACH

Two main controllers are developed in this work, namely Lambda Controller and Maximum Brake Torque Timing controller. The control approach used for each controller is discussed below.

LAMBDA CONTROL

This part is divided into three different parts: system identification and modeling, validation of the model and finally design of the controller.

System identification and Modeling

A dynamic model is essential to a MPC controller. A model is needed to be able to predict the future behavior of the system. Injection duration and throttle position are used as input parameters and lambda is an output parameter of the model.

System identification is used to obtain a black box model. The system was excited with Pseudo-Random Binary Sequence (PRBS) signals for injection duration and throttle position and data was collected. The system Identification Toolbox in Matlab named *Ident* was used to construct a model of the dynamic system from measured input-output data. It uses a combination of subspace-based identification and optimization of prediction error which proved to generate a good model.

A 3rd order discrete time state space model was designed. The injection duration is between 3-6 ms and throttle position between 40-50 % (opening) at 1000 RPM. Figure 2 shows how the modeled lambda follows the measured lambda. Offset is removed from the data.

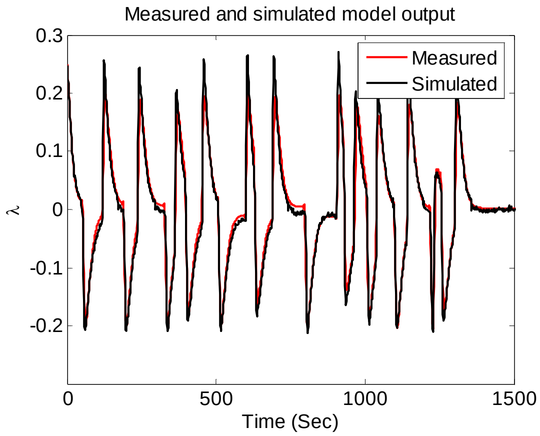

Figure 2: System identification of lambda by PRBS signals

Model Validation

The dynamic model must be validated before using in a controller. The model was designed at 1000 RPM and 40-50% throttle opening. It is validated by data from 800 RPM 30-40 % opening (see Figure 3). The result shows that the model can capture the lambda dynamics with very good precision.

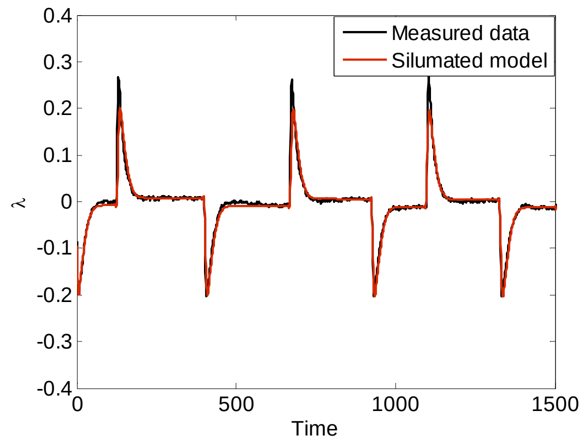

Figure 3: Validation of the lambda model

Design of the Lambda Controller

Throttle position is used as a "*measured disturbance"* and injection duration as "*manipulated variable*" (see Figure 4). When a parameter is defined as measured disturbance it means that the controller should provide feedforward compensation based on the measurement. A manipulated variable is a signal that will be adjusted by the controller, i.e., in this case injection duration which will by controlled by injectors. An input parameter in Figure 4 named "*Unmeasured Disturbance*" is a disturbance for which the controller will provide feedback compensation. An *Unmeasured Disturbance* can be some parameters like engine speed or EGR rate.

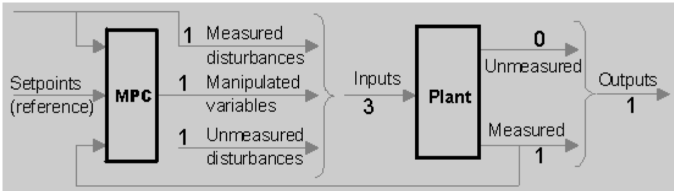

Figure 4: MPC Controller structure

There are a number of tuning parameters to be used when designing a MPC controller, such as: weights, constraints, estimation gain etc. The proper constraints on manipulated variables e.g. injection duration were set. The output constraints were chosen between [-0.04 0.03] from the set value which is 1. This means that the lambda is allowed to be between [1.03 0.96]. This interval was chosen in order to prevent high level of NOX or HC emissions.

MBT TIMING CONTROL

For each operating condition of the engine optimal spark timing can be obtained. This optimal spark timing is called maximum brake torque (MBT) timing, which maximizes the output load and the efficiency of the engine and thereby lowers the fuel consumption.

CA50 is an engine crank position in Crank Angle Degree (CAD) at 50% heat release. Figure 5 shows how changes in CA50 position affect load, efficiency and thereby the Specific Fuel Consumption (SFC). MBT is obtained roughly when CA50 is 10 degrees After Top Dead Center (ATDC).

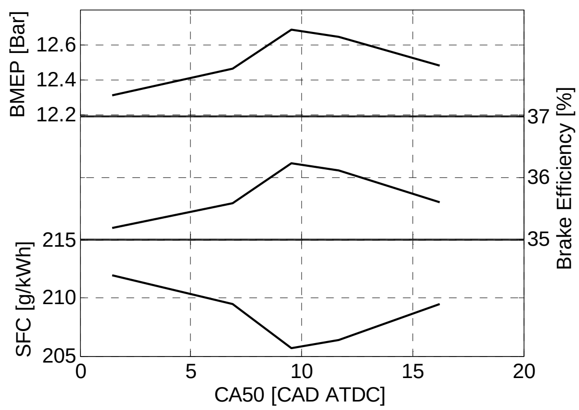

Figure 5: Effect of ignition timing on Brake efficiency and SFC

CA50 is almost unique for each operating condition (see Figure 6). It means that it is essential to have control of MBT timing during the transients in order to achieve the lowest SFC. Traditionally MBT timing is implemented as an open-loop control where the ignition timing is found by using a static lookup tables.

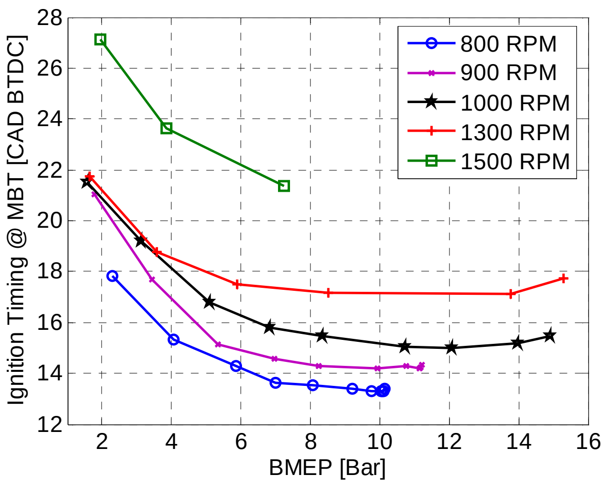

Figure 6: MBT timing for different loads and speeds

<u>Design of the MBT Controller</u>

A PI regulator was designed to control the MBT timing. The closed loop MBT control evaluates the calculated CA50. The error signal is based on the difference between the calculated CA50 and a predefined CA50 (i.e. CA50=10) and, an ignition offset was generated from that for each cylinder. The individual ignition timing was adjusted by the regulator to keep the CA50 at the same level as the desired CA50. Bumpless transfer and Anti-Windup algorithms were applied during the design of the regulator.

RESULTS

This section is divided into two parts because of the two developed controllers. In the first part the results during development of the MBT controller is discussed and in the second part the results for the lambda controller are discussed.

MBT CONTROLLER

The engine is operated at different operating condition (different speeds and loads) and during these tests the MBT controller was active and performed well. Figure 7 shows how a PI regulator can improve CA50 balancing in all cylinders. The engine is operated at engine speed 1200 RPM and 8 bar Brake Mean Effective Pressure (BMEP).

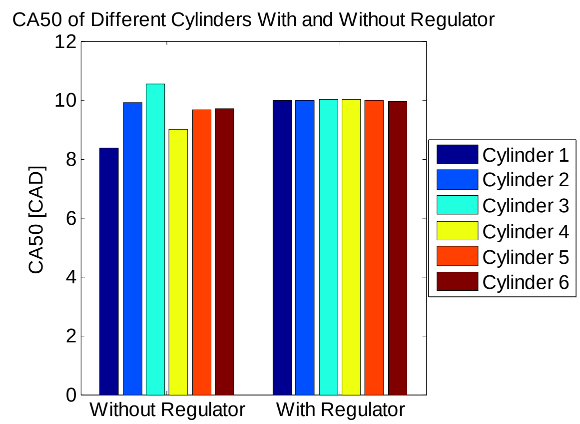

Figure 7: CA50 of all 6 cylinder with and without MBT Controller

Step changes in load are performed in order to investigate the performance of the MBT controller. Figure 8 shows that when opening the throttle position from 30 to 60% (which corresponds roughly to 3 to 11 BMEP at 1200 RPM), the ignition timing of each cylinder is adjusted by the MBT controller in order to keep CA50 equal to 10. Figure 8 also shows that an overshoot occurs in CA50 which is a result of the sudden change in throttle. The controller tries to compensate the error immediately which results in an overshoot. This overshoot can be minimized by using a lookup table as a feedforward map coupled with the feedback controller. Feedforward is a control technique that can be measured but not controlled. The disturbance (i.e. throttle changes) is measured and fed forward to an earlier part of the control loop so that corrective action can be initiated in advance of the disturbance having an adverse effect on the system response. Data for creating the feedforward map is collected from running the engine at different operating conditions (see Figure 6). Figure 9 shows that the overshoot is minimized by using the feedforward map. It is also obvious in the figure that the controller with feedforward responds more quickly to the disturbance.

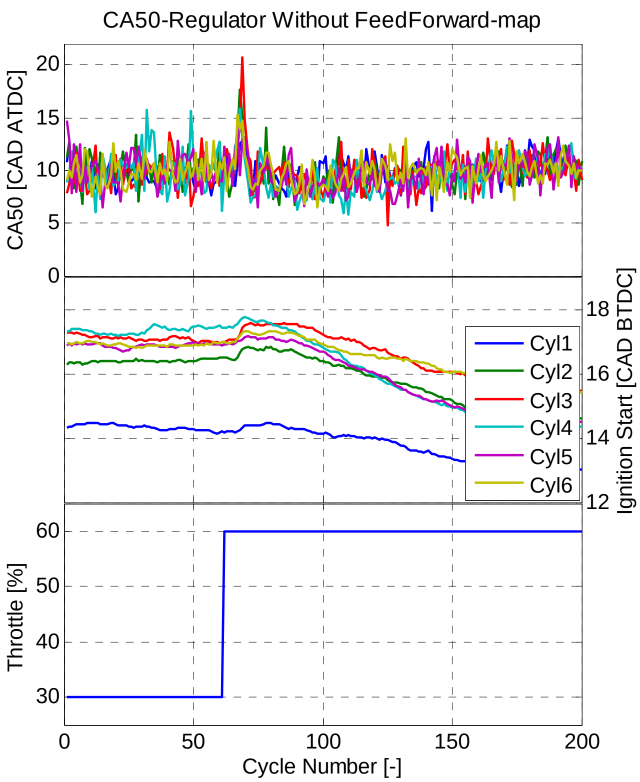

Figure 8: Individual ignition control (Feedback control) with load step change @ 1200 RPM

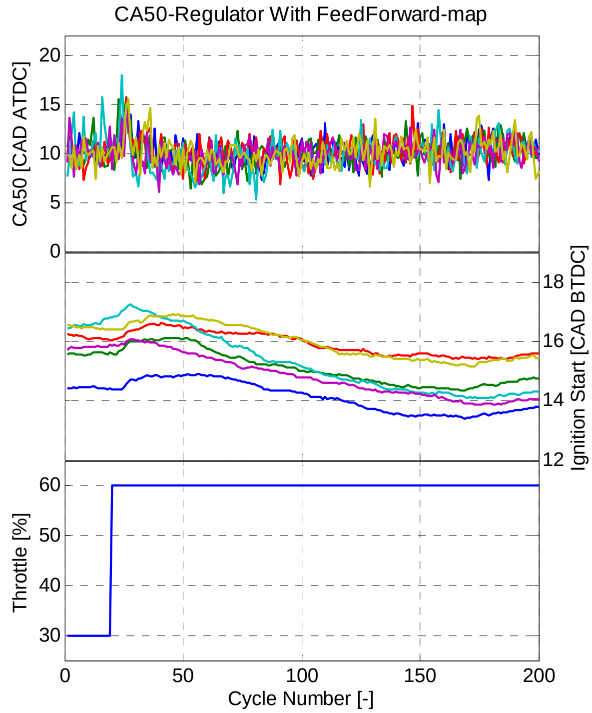

Figure 9: Individual ignition control (Feedforward + Feedback control) with load step change @ 1200 RPM

LAMBDA REGULATION

The performance of the developed MPC lambda controller is tested by generating different disturbances. These disturbances are step changes and ramp changes in throttle position i.e. load transients, step changes in speed and EGR are also made to investigate the quality of the MPC lambda controller. The lambda controller is also tested with step changes outside the range of the designed model. The results of these tests are presented in the following subsections. The reference lambda in these tests is 0,995 which represent the best trade-off for the catalyst used in these tests.

THROTTLE DISTURBANCE

Figure 10 shows the response of the controller and the emissions of HC and NOX when applying step change in throttle position. Since the emission measuring system is not fast, some delay is seen in the plot. The emissions are measured after the catalyst. Lambda is close to the defined constraints but it does not exceed. In Figure 11 ramp changes in throttle are applied and the controller follows the changes very well. In order to see how the controller works outside of the range of the model, some tests are also performed. The model is designed at 1000 RPM, throttle [40 50%] and injection duration [3 6] millisecond. In Figure 12 a wider throttle change than the model validation range is applied. The emissions do not exceed the limits. Figure 13 shows throttle changes at lower engine speed i.e. 800 RPM. It shows that lambda exceeds somewhat the constraint for some cycles. This can be solved by introducing engine speed as another input into the model and apply feedforward based on the measurement. This is planned as future work.

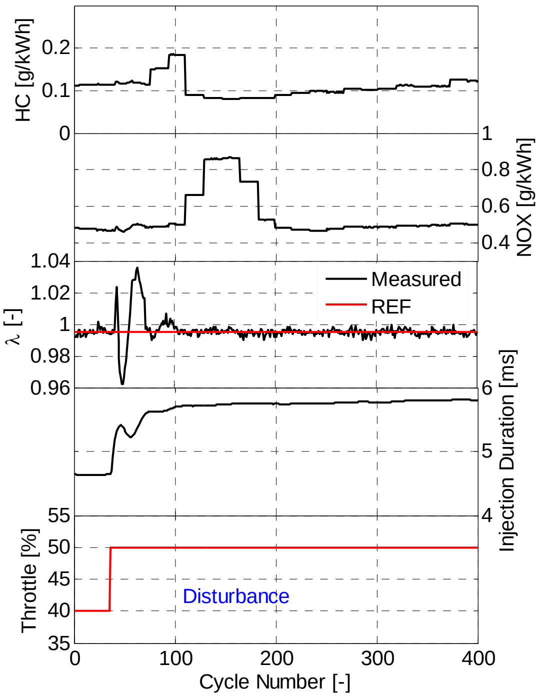

Figure 10: Results of the MPC lambda controller with step change of the throttle inside the model range

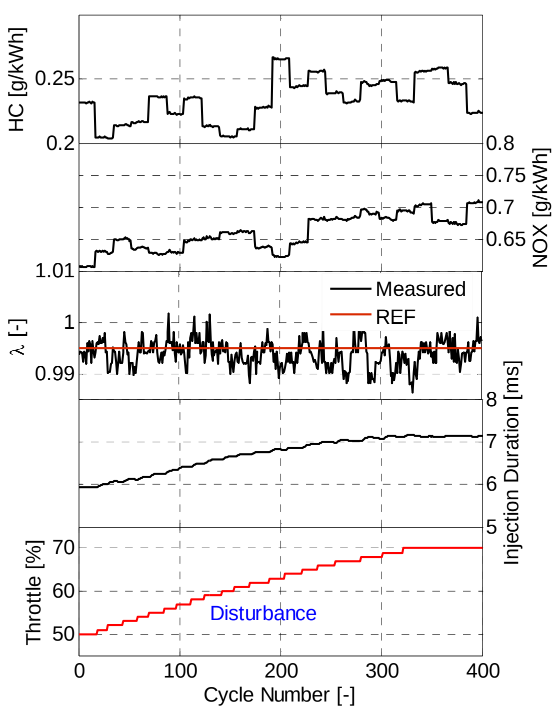

Figure 11: Results of the MPC lambda controller with ramp change of the throttle in the model range

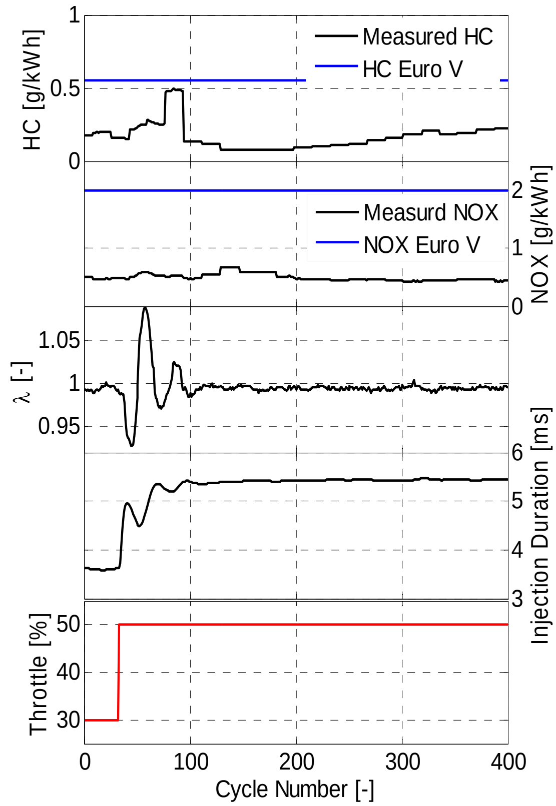

Figure 12: Results of the MPC lambda controller with step change of the throttle outside of the model range [30 50%]

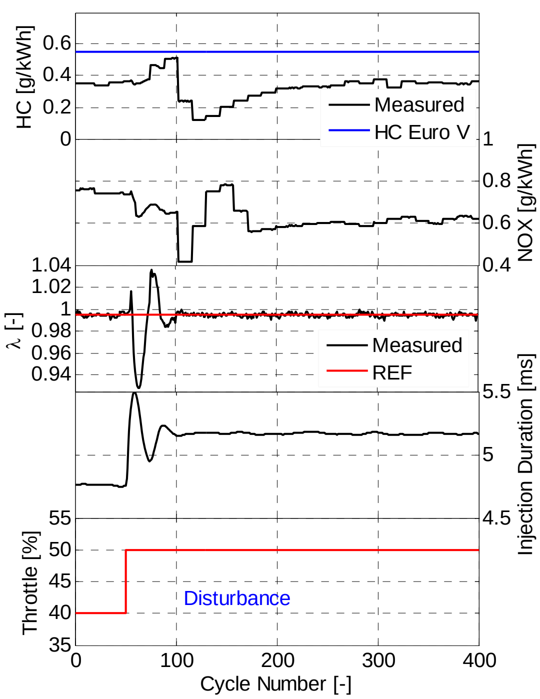

Figure 13: Results of the MPC lambda controller with step change of the throttle out of the model range @ 800 RPM

SPEED DISTURBANCE

In Figure 14 a rapid decrease in engine speed is applied. The controller manages this transient well and the emissions are not affected significantly. Again, further improvement is possible by including engine speed as a measured disturbance.

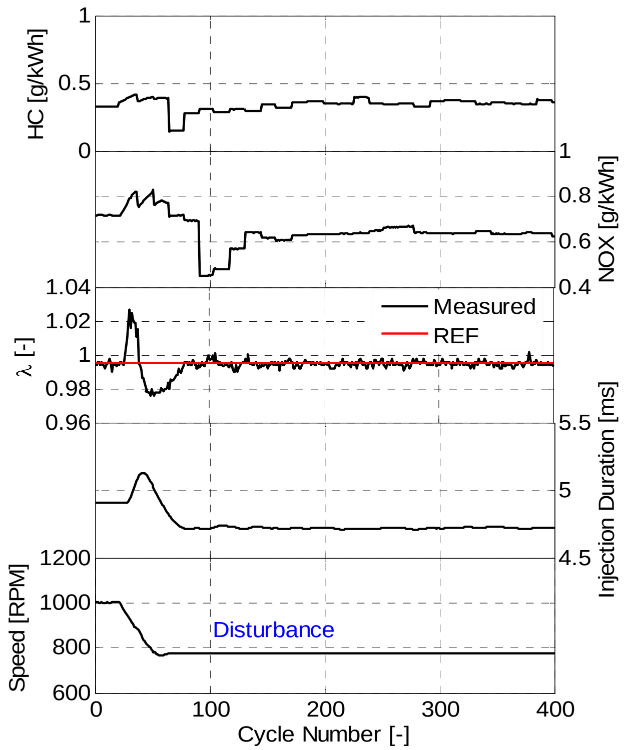

Figure 14: Results of the MPC lambda controller with step change of the speed in the model range

EGR DISTURBANCE

In Figure 15 a rapid change in EGR level is applied in order to see if the lambda controller can manage this kind of disturbance. Since the EGR measurement is slow and takes a couple of seconds it is decided to plot only the changes in EGR valve position. At this point the amount of EGR was increased from 1 to 10 percent. Figure 15 shows that lambda exceeds slightly the constraints and thereby HC emission exceeds slightly the limit for some cycles. This can be improved by using a model which has the EGR valve position as input parameter.

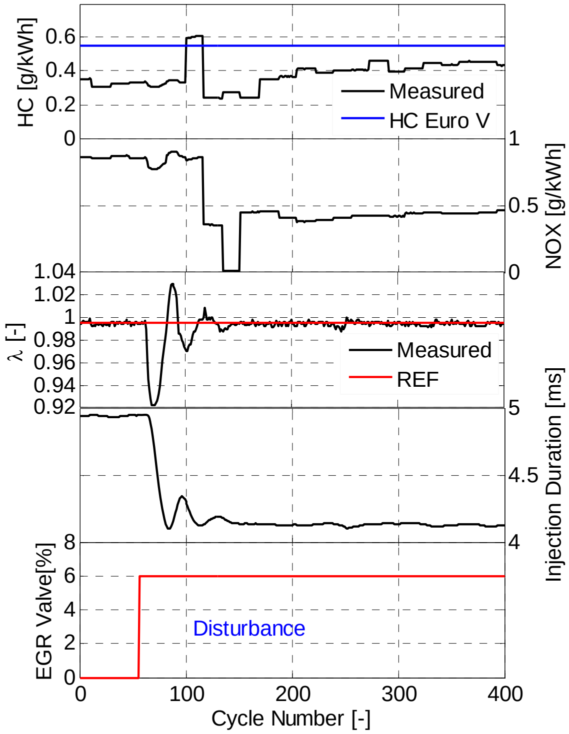

Figure 15: Results of the lambda MPC regulator with step change of the EGR in the model range (10 % EGR rate)

PI VERSUS MPC LAMBDA CONTROLLER

Before using the MPC lambda controller a traditional PI lambda controller was used for controlling the overall Air/Fuel ratio. In this part the same tests which were performed with the MPC controller are applied with the PI controller. In Figure 16 a rapid but not too big throttle change is applied. The results show that the lambda goes up to 1,06 which results in a big increase in NOX emissions. Figure 10 shows the results of the same experiment performed with the MPC regulator. By using an MPC regulator the feedforward calculation helps to find the right amount of fuel injection faster.

In Figure 17 a bigger change is applied to the throttle. Comparing Figure 12 with Figure 17 shows how much better the MPC controller manages this type of transient than the PI controller.

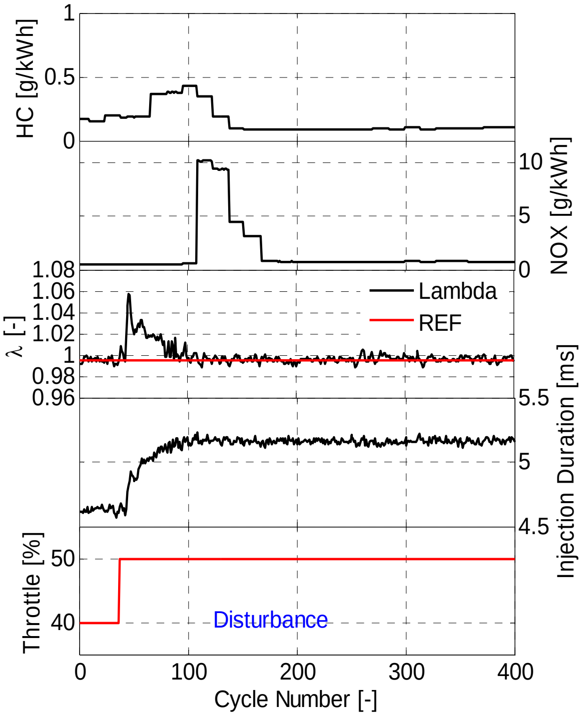

Figure 16: Results of the lambda PI regulator with step change of the throttle

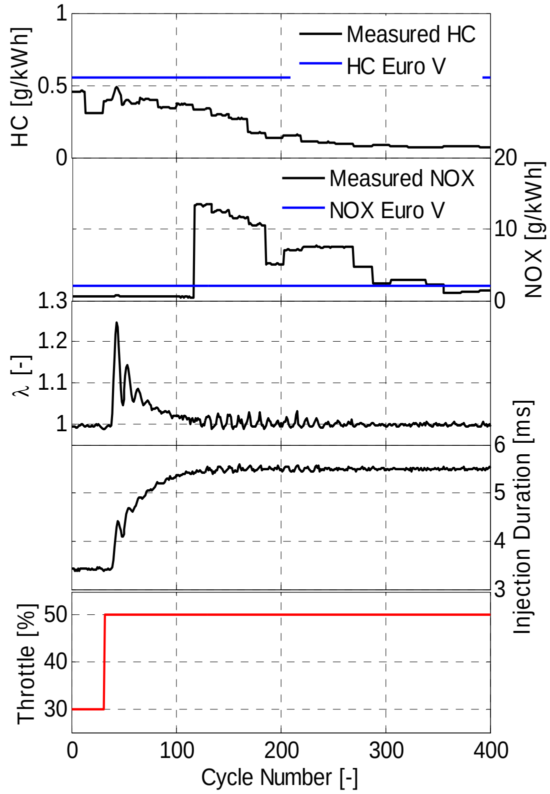

Figure 17: Results of the lambda PI regulator with step change of the throttle

CONCLUSION

Two main controllers are developed in this study. A combination of a feedforward map coupled with a PI closed loop controller is developed to control MBT timing. Model Predictive Control is also developed to control the overall Air/Fuel ratio. The main conclusions obtained from this study are as follows:

1. Using a static feedforward map coupled with a PI closed loop controller showed excellent performance for controlling MBT Timing.

2. System identification made it possible to make a reliable dynamic model of lambda. Injection duration and throttle position were the two input parameters of this model.

3. Model Predictive Control was shown to be a suitable method for controlling lambda.

4. MPC lambda controller is compared with PI lambda controller and MPC showed to be a better choice than PI for controlling lambda.

5. The results show that rapid increase in engine speed and EGR rate makes the quality of lambda control deteriorate. Including engine speed and EGR rate as input parameters to the model can improve the results.

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