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Two-Stage Turbocharged Gasoline Engines: Experimental Validation of Model-based Control

Thivaharan Albin * **Dennis Ritter** * **Norman Liberda** **
Stefan Pischinger ** **Dirk Abel** *

* *Institute of Automatic Control, Prof. Dr.-Ing. D. Abel, RWTH Aachen University, 52074 Aachen, Germany (corresponding e-mail: T.Albin@irt.rwth-aachen.de).*
** *Institute for Combustion Engines, Prof. Dr.-Ing. S. Pischinger, RWTH Aachen University, 52074 Aachen, Germany (corresponding e-mail: liberda@vka.rwth-aachen.de).*

Abstract: For increasing the efficiency of combustion engines new, increasingly complex air path concepts are viable. In case of gasoline engines one promising technology is the two-stage turbocharging. The closed-loop control of this air path concept is topic of the present paper. For this reason a model-based predictive control approach based on a piecewise affine model is investigated. It has the advantage of taking the multiple input process behavior into account, compensation for the arising dead time and respecting the turbocharger speed limits, with low demands on the calibration effort. For validating the control algorithm the investigated air path concept was installed in a vehicle and the proposed control algorithm was implemented on a prototyping control unit. In the present paper the results of the vehicle experiments, conducted on the road, are demonstrated. For validation purposes several tip-in maneuvers are demonstrated exemplary.

Keywords: Internal Combustion Engine, Model-based Predictive Control, Air Path Control

1. INTRODUCTION

Continuous improvements of gasoline engines still allow further reduction of CO_2 emissions, while achieving same level or even reduced level of pollutant emissions. Among others, improvements of the combustion process, the air path or the exhaust gas after treatment are possible (Payri et al. (2014)). In regard of the air path, the inclusion of charging devices offer the possibility of increasing the charging pressure which allows for the so-called 'downsizing' of engines. With 'downsizing' the same or even a higher nominal power can be achieved, despite the reduction of engine displacement which results in an increase of efficiency.

Recent research investigates on different charging concepts for the air path. One of the main goals is to mitigate the trade-off between a high specific power on the one side and fast transient raise of the charging pressure on the other side. A possible solution is the use of more variability in the charging device, e.g. by using variable turbine geometry or two-stage turbocharging. These complex charging devices make a closed-loop controller necessary. An overview on basic modeling and control of turbochargers is given in Eriksson and Nielsen (2014).

In gasoline engines the two-stage turbocharging is a future promising technology. The architecture consists of a small high-pressure stage, which is capable of realizing the demanded high dynamic transient response and a large low-pressure stage for realizing high specific power. In this paper the closed-loop control of this concept is investigated. The control algorithm needs to handle both turbocharger stages, such that disturbances are rejected and reference tracking for the charging pressure is made possible. For gasoline engines quick reference tracking has to be achieved without oscillations and without significant overshoots, as the charging pressure directly correlates to the driving torque. The reason lies in the quantitative control used as working principle for gasoline engines, which results in the need for a fixed air-to-fuel ratio and thus the torque is determined by the air path. In diesel engines oscillations can be tolerated to a certain amount, as the driving torque is determined by the fuel path. This is due to the qualitative control used as working principle for diesel engines, which allows for variations in the air-to-fuel ratio and therefore also allows to decouple torque and charging pressure up to a certain amount. On top the control algorithm should respect the upper limit constraints for the high-pressure and low-pressure turbocharger speeds, as exceeding these limits might damage the turbocharger. This becomes especially challenging, as the exhaust gas temperatures are very high, such that the limits can be reached relatively quickly and the turbocharger speed is typically not measured in a series-production configuration.

Compared to gasoline engines, the research of air path concepts in diesel engines is more mature. For diesel engines the two-stage turbocharging was already successfully

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applied (see Moulin and Grondin (2013)). However, even for similar air path concepts, the control concepts of diesel engines cannot be directly incorporated for gasoline engines as the control requirements as well as the controlled system dynamics are different, as explained earlier. For gasoline engines the closed-loop control for one-stage turbocharging with wastegates was demonstrated, see Moulin and Chauvin (2011). In case of two-stage turbocharging only a limited amount of publications is available. Thomasson et al. (2013) treat the analysis and modeling of the pneumatic actuators in this setup. In Glueck (2013) a state-of-the-art implementation of the two-stage turbocharging concept is given, including validation in a vehicle. In that paper a SISO (single input single output) closed-loop PID controller is proposed. For lower engine speeds only the high pressure stage is controlled (low pressure wastegate is fully open) and for higher engine speeds the low pressure stage is controlled (high pressure wastegate fully open). In a medium engine speed range, one of the two actuated variables is used in a feed-forward manner with look-up tables. Compared to that, a multiple-input model-based predictive control (MPC) concept offers several advantages. It allows for coordinated MISO (multiple input single output) control, inclusion of dead-times and inherent consideration of turbocharger speed limits. On top the model-based approach allows for reduction of calibration time compared to the heuristic, look-up table based approach.

Previous work of the authors about this air path concept is given in Albin et al. (2015). In Albin et al. (2015) a simulation model of the process was derived and the control algorithm was validated in simulation. The main contribution of the present paper is the experimental validation of the MPC algorithm, which is based on a piecewise affine (PWA) model. The validation is done in a vehicle on the road, such that the overall system without any simplifications can be evaluated. For this reason the control algorithm was adapted such that it is real-time capable and was implemented on a rapid prototyping unit. Additionally the control algorithm was improved from a classical MPC towards a 2-stage MPC algorithm.

The paper is organized as follows. Section 2 introduces the setup of the investigated air path concept. The resulting full model of the process and the PWA approximation of the model are detailed in section 3. In section 4 the control algorithm consisting of a Kalman-Filter and the MPC concept are explained. The validation of the concept in a vehicle with tests on the road are depicted in section 5.

2. TWO-STAGE TURBOCHARGED GASOLINE ENGINE

2.1 System Set-Up

Fig. 1 shows the schematic set-up of the investigated air path architecture. This set-up consists of two turbocharging stages that are placed in series. Each stage consists of a compressor and a turbine that are connected by a common shaft. The architecture depicted was built up and implemented in a demonstrator vehicle (Ford Focus) with a 1.8 l 4-cylinder engine. The experiments conducted in this paper have been recorded with this demonstrator vehicle. In Glueck (2013) and Buchner et al. (2011) a more detailed overview on the system is given.

The controlled variable of the system is the charging pressure $p_{charging}$ [1], which is measured with a pressure sensor, positioned behind the intercooler and in front of the throttle valve. Due to the high exhaust gas temperatures in gasoline engines the application of sensors and advanced actuators in the exhaust gas path is critical for a series production configuration. Thus, in the presented control approach no sensor signals from the exhaust gas path are used for control purposes.

As actuators, wastegates on the high-pressure ($u_{wg,hp}$) and on the low-pressure stage ($u_{wg,lp}$) are used. Electronic wastegates have the advantage that they have a position feedback-sensor and thus allow for accurate setting of the valve opening. However, in the demonstrator vehicle used, as alternative, cheaper pneumatic actuators are applied, without any additional sensor e.g. for position feedback. The wastegate actuation signals correspond to a pulse-width modulated (PWM) signal, which can be set between $u_{wg,hp} = [0...100]$ and $u_{wg,lp} = [0...100]$. These allow to manipulate the pilot pressure, which has influence on the cross-section diameter of the opening area. Thus, the amount of exhaust gas which passes the turbine or the wastegate can be adjusted.

2.2 Control Algorithm

For the chosen control approach the two wastegate PWM-signals $u_{wg,hp}$ and $u_{wg,lp}$ are used as actuated variables and $p_{charging}$ is used as controlled variable. The additionally used measured variables, the engine speed n_{eng} and ambient pressure p_{amb} are both available in a series-production configuration. For the purpose of modeling and validation of the control algorithm additional sensors are available in the car, however they are not used in the control algorithm. Especially, both turbocharger speeds and the pressure between the compressors (resulting in the pressure ratio over the two compressors) are measured in the demonstrator vehicle for modeling and validation purposes, but are not used as input for the control algorithm.

As nowadays usual in series applications the throttle valve is fully open in charged operating points to reduce fuel consumption. In consequence, the charging pressure is equal to the intake manifold pressure and directly correlated to the torque of the engine. The set point for charging pressure is determined by the requested torque in a conventional manner, as given in torque oriented engine control structures. For the investigated maneuvers, the high pressure bypass valve is always closed as the paper focuses on the evaluation of the control quality when both turbochargers are active. All other parameters of the engine control structure, such as ignition, injection, camshaft position are equal to the standard calibration. In the presented control concept the focus is set on closed-loop control of the charging pressure by actuating the high-pressure and low-pressure wastegate.

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[1] For better overview all variables and indices are summarized in Table A.1 in the appendix section.