SCIENCE CHINA
Information Sciences

• RESEARCH PAPER •

July 2018, Vol. 61 070204:1–070204:11
https://doi.org/10.1007/s11432-017-9342-7

Special Focus on Learning and Real-time Optimization of Automotive Powertrain Systems

Benefits of model predictive control for gasoline airpath control

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Received 21 November 2017/Accepted 29 December 2017/Published online 14 June 2018

Abstract One effective possibility to reduce pollutant emissions and fuel consumption of an internal combustion engine is the use of improved process control. It is made viable by the implementation of additional actuators and sensors which allow to operate the process more flexible. For full exploitation of the setup an appropriate control algorithm is necessary. Classical engine control structures rely on the use of many calibration parameters which result in high demands on the calibration time. Model predictive control (MPC) is an advanced control algorithm which is able to overcome this drawback. It allows to use a mathematical plant model for control synthesis which reduces calibration time and makes reusability possible. The present paper introduces the MPC algorithm and discusses the benefits of MPC for engine control. A special emphasis is put on the application for gasoline airpath control. For clarification, the benefits are demonstrated by numerical simulation studies. For the example of gasoline two stage turbocharging, the advantage concerning control performance are shown as well as the possibility to easily adapt to changed specifications for the closed-loop control dynamics.

Keywords model predictive control, engine control, airpath control

Citation Albin T. Benefits of model predictive control for gasoline airpath control. Sci China Inf Sci, 2018, 61(7): 070204, https://doi.org/10.1007/s11432-017-9342-7

1 Introduction

Internal combustion engines (ICE) play a dominant role in the mobile and stationary energy supply of the society. In the foreseeable future, ICEs will continue to play a major role1). This holds true even though increasing electrification of the propulsion system and increasing shares of renewable energy can reduce the relative amount of ICEs for the energy supply. This poses the challenge to continue reduction of fuel consumption and pollutant emissions, such as nitrogen oxides (NO$_x$), carbon monoxide (CO), hydrocarbons (HC) and particulate matter (PM), also known as soot. This development has to be achieved while sustaining the recent level of comfort and power as well as being cost-effective.

To meet these requirements all aspects of the combustion engine are revisited. Examples include the combustion process, the airpath, the exhaust gas after-treatment, waste heat recovery and auxiliary devices (see [1]). One of the investigated measures is the improvement of the process control which is achieved by adding new sensors and actuators to the setup. Recent engines are equipped with 15 to 25 sensors and actuators with 5 to 9 manipulated variables [2]. In case of the airpath new setups are investigated which are characterized by the possibility of improved adaptation to the recent operating

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1) International Energy Agency. Energy technology perspectives 2016. http://www.iea.org/etp/etp2016/.

conditions. This includes the use of turbocharges with multiple stages, exhaust gas recirculation loops with multiple stages and also variable valve actuation.

Due to this increased amount of actuators and sensors also the control algorithm has to cope with the new complexity. Only if the control algorithm is able to fully exploit the given possibilities, benefits in terms of fuel consumption and pollutant emissions result. For appropriate control of the engine, several requirements have to be addressed. Three categories can be named for the requirements: (1) control performance; (2) protection against damage; (3) non-functional requirements.

Challenges to fulfill these requirements are especially given by the (open-loop) system properties: (1) multiple-input multiple-output (MIMO) system setup; (2) nonlinearity; (3) stiff system dynamics; (4) dead-time; (5) highly dynamical system; (6) limitations on the actuator; (7) noise on the measured signals.

Due to the highly dynamic system, the control loops are usually running with very small sampling times. Additionally the engine is operated at different ambient conditions which concern temperature, pressure, humidity. Thus, the engine control should be robust enough to cope with (unmodeled) disturbance.

The conventional solution for engine control is based on the application of look-up tables. Look-up tables define parameters for the feedforward and feedback control based on the recent operating point. At the moment, more and more functionality in engine control is implemented via the use of mathematical models, especially in the feedforward path. The main benefit of using mathematical models is the possibility to drastically reduce calibration time and the reusability of the developed control algorithms in other engine control projects.

In this paper the use of model predictive control (MPC) is evaluated for use in engine control problems. MPC offers the advantage to simultaneously feedforward and feedback control by the use of a mathematical model of the process. This allows to reduce calibration time and the reusability of the generated models. For this reason an introduction to MPC is given along with application examples. Section 2 introduces engine control based on MPC. Section 3 demonstrates the application of MPC for the airpath control in gasoline engines. Section 4 exemplifies the benefits with a numerical case study for a gasoline two stage turbocharging system. Instead of focusing on the details of the NMPC controller, the advantages and possibilities of NMPC are demonstrated.

2 Model-based engine control via predictive approach

2.1 Model-based engine control

General control algorithms can be divided in three categories:

(1) Controller design and synthesis without the use of a model (e.g., iterative learning control, extremum seeking control);

(2) Controller design and synthesis (offline) by use of a model (e.g., H-inf control, pole placement);

(3) Controller itself contains a model of the process (e.g., internal model control, flatness-based control, model predictive control).

Obviously there are no sharp borders between these three categories. Just to mention two examples: a PID-controller which is heuristically tuned at the testbench would fall into category 1, whereas a PID-controller which is synthesized by a model would rather fall into category 2. The iterative learning control can be improved by consideration of model knowledge such as deadtime [3]. There is no strict definition of the term model-based controllers. However, in the following, the controllers of category 3 (and only these) are considered as model-based controllers. The direct use of a mathematical model within the control algorithm allows an integrated systematic control development.

Model-based controllers achieve high control performance, especially in the case of complex systems, i.e., nonlinear MIMO systems with strong coupling between the different in- and outputs. The model-based approach has the advantage that the nonlinearity and the coupling of the different components are known which allows to account for the specific behavior. Due to the systematic control design the high performance can ideally be achieved without the need for excessive measurement data and thus reduces development time and cost.

The advantages of model-based control in terms of control performance, systematic design, reduction of calibration effort, etc. are very meaningful for engine control. Consequently, there is a big benefit of using model-based control for engine problems. Each control technique has own advantages and disadvantages. Often the control algorithms are suited for a certain class of system dynamics. The arising control problems in ICEs are quite diverse. The change of the physical location of an actuator might result in a change of the system dynamics, e.g., going from no dead-time to a considerable dead-time. It might happen, that a control algorithm which was appropriate before-hand is not appropriate any more. For the systematic design, it is preferable if the control algorithm is employable independent of the setting. In this context MPC has an superior advantage: it is almost independent of the investigated system dynamics. Additionally, it allows for systematic consideration of process/safety limitations. As consequence MPC is suited best to realize a plug-and-play control.

The major drawback of the MPC algorithm (and many other model-based control approaches) is the computational burden of the control algorithm. This leads to increased requirements on the hardware side. Looking at it on the longterm, the hardware of electronic control units will become more powerful, while the price for the hardware decreases. At the same time the advantages given by the ability to handle complex MIMO system with reduced calibrational effort will get more and more important. As consequence MPC has high potential for future use in ICEs. In next subsection the concept of MPC is depicted.

2.2 Model predictive engine control

The MPC relates to a class of control strategies which explicitly utilize a mathematical process model of the controlled application. Based on the model, the system output behavior is predicted which allows computing an optimal input sequence by minimizing a cost function subject to constraints. The cost function defines the control strategy. An optimal open-loop control sequence of the inputs is the result of the optimization which is calculated in every sampling step. Due to limitations on the maximum calculation time, the outputs of the model are predicted over a finite prediction horizon. The recent value of the optimal inputs is put out to the process. In the next sampling step, the cost function is solved again and a new control sequence is calculated over a shifted prediction horizon. This procedure is called receding horizon principle. In the special case of a nonlinear system model, constraints or cost function the method is called nonlinear model predictive control (NMPC).

Compared to classical control structures the feedforward and feedback action are combined in a single controller. Typically the MPC is used as a state-feedback controller which means that the control action is based on the recent states of the system. Either the system states are all measurable or if they are not, a state observer has to be applied to estimate the system states. These states are necessary, as they are used for the prediction of the output values in the process model. Successful implementation of MPC comprises three ingredients [4]: (1) (reduced-order) process model; (2) suitable formulation of a cost function; (3) real-time feasible optimization algorithm.

These three parts have to match each other such that real-time feasible control is achieved which fulfills all arising requirements. For systems with large sampling times the real-time feasibility is not an issue, but for systems with faster dynamics, the computational demand is the major bottleneck for applying MPC algorithms. This is the reason why the MPC algorithm was originally limited to relatively slow varying applications. Typical applications have been in the chemical industry and refinery. In [5], the automotive applications play a negligible role. In the last two decades the computation time of MPC has been reduced drastically. The reasons can be found in improvement of methods and algorithms such as for numerical optimization and improved hardware [6]. With the reduction of computation time, it is now possible to apply the control law to systems with fast system dynamics [7, 8]. The application to control problems in the automotive area is now also feasible [9]. Within the field of automotive control, engine control problems are among the areas of focus.

3 Overview on airpath control

The task of airpath control in a combustion engine is to deliver the right amount and the right composition of gas entering the combustion chamber. Beside fresh air the gas entering the combustion chamber can also contain recirculated exhaust gas. The fundamental principle of a gasoline engine is the combustion of a stoichiometric mixture of gasoline fuel and air. As consequence the torque is directly correlated to the amount of fresh air. In a very basic setup of a gasoline engine only a throttle is needed in order to deliver the right amount of fresh air which has to be controlled depending on the required torque. The diesel engine works on the principle of lean combustion. The diesel engine is operated with excess fresh air and the torque is adjusted by the amount of injected fuel. In the most basic naturally-aspirated diesel engine setting, no additional component for airpath control is needed.

These basic setups are usually not satisfying the demands of modern engines concerning transient performance, pollutant emissions and also fuel efficiency. For this reason, additional components are integrated to improve the air handling. Among these are components such as turbochargers, exhaust gas recirculation and variable valve timing. With these additional components in the airpath the control is also getting more complex. As the components are interconnected, a control is advantageous which considers the behavior with coupled multiple inputs. Due to the inherent differences in diesel and gasoline engines, e.g., concerning the air-to-fuel ratio, it is difficult to transfer a gasoline engine controller to its diesel counterpart. For this reason the airpath control of gasoline and diesel engines have to be investigated individually.

3.1 Airpath technologies

In the following an overview on two technologies, the turbocharging and the exhaust gas recirculation are given. Based on that a survey is conducted for MPC based control of gasoline engine airpath.

3.1.1 *Turbocharging*

One investigated concept to reduce fuel consumption and emissions is the application of ‘downsizing’ by the use of turbochargers. The goal of downsizing is the improvement of the engine operating points while maintaining the same engine power. With turbochargers the engine size can be reduced without impairing in terms of engine power. The reduction of engine size leads to a reduction of friction losses and for SI engines the throttle can be opened more widely which reduces the pumping losses. For maintaining the same engine power, the turbochargers allow to extract energy from the hot exhaust gas in order to compress the intake air of the combustion engine to higher pressures than achievable with a naturally aspirated engine. Specifically this is achieved by a turbine located in the exhaust path which is connected to a compressor in the intake path with a common shaft. For being able to adjust the turbocharger to the specific operating point, variability is introduced in the concepts. This might be the case by the use of wastegates on the turbine side or the use of variable turbine geometry. As a direct coupling between intake and exhaust path exists, the control of the process is a crucial task. Typical architectures with single stage and two stage turbocharging are depicted in Figure 1.

3.1.2 *Exhaust gas recirculation*

An additionally used measure for improvement of the engine performance is the exhaust gas recirculation. In this case, a composition of burned gas and fresh air is used for the combustion process. Specifically following advantages of exhaust gas recirculation can be named for gasoline and diesel engines: (1) lower peak combustion temperatures and thus lower NO_x emissions (especially relevant for lean stratified engines); (2) dethrottling; (3) knock reduction; (4) lower exhaust gas temperatures (protection of components); (5) thermodynamical advantageous properties of the charge; (6) noise reduction.

A good overview on the advantages of EGR in a gasoline engine can be found in [10]. Valves are added in the airpath for controlling the amount of exhaust gas recirculation. These valves allow to generate a pressure difference and thus to control the gas flow to the intake manifold.

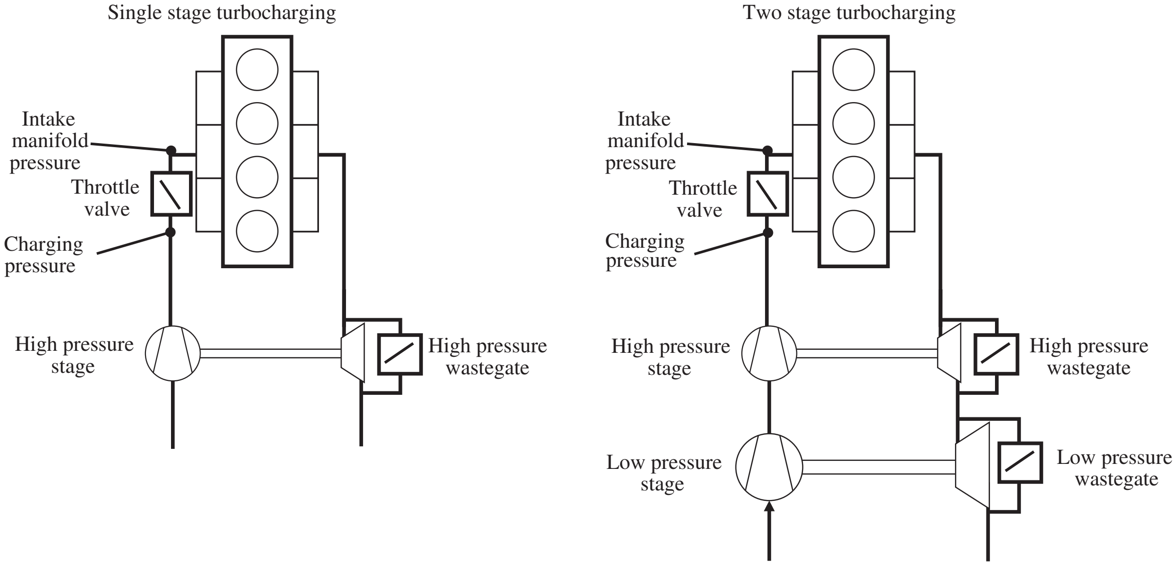

Figure 1 Setup of single stage turbocharging and two stage turbocharging.

3.2 Survey on MPC based airpath control for gasoline engines

In the following a literature review is conducted on the topic of MPC for turbochargers in airpath control for gasoline engines.

3.2.1 *Single stage turbocharging*

Several MPC approaches have been investigated for the single stage turbocharging architecture. In this case a throttle and a wastegate are combined to control the amount of fresh air which is trapped in the cylinder. Ref. [11] describes the control of the intake manifold pressure by considering the wastegate and the throttle simultaneously. For this purpose a neural network is used as controller internal model. Measurement data has been recorded for the use of system identification of the neural network. As control concept a linear MPC feedback controller is used where the model for prediction is gained via linearization in every time step. Ref. [12] also uses linear MPC where the prediction model is gained via linearizarion in every timepoint. However, in this case a physical-based nonlinear model is used. As controlled variables the air mass flow and the charging pressure are applied and as actuated values the throttle and wastegate are installed. The research shows the robustness against differences in cam phasing position from a nominal operating point is given with the MPC control action. Ref. [13] considers an architecture where the combination of wastegate and throttle are used for the control of the intake manifold pressure. In this research the more elaborate NMPC is used for the control task. A physical model is built up for the use as controller internal model. To realize real-time feasibility of the NMPC algorithm, laguerre functions are used to reduce the number of optimization variables. Refs. [14,15] use the physical model to calculate an explicit NMPC controller which has the advantage that no online optimization has to be performed. On top of controlling the intake manifold pressure, the MPC is also used to increase efficiency of the operating points. The efficiency optimization is conducted by minimization of the ratio between exhaust back pressure and intake manifold pressure. As two controlled inputs are present, the intake manifold pressure can be controlled by various combinations of the two actuators. The MPC allows to use the one combination which is most efficient.

3.2.2 *Two stage turbocharging*

In [16], a high-pressure (HP) and low-pressure (LP) wastegate are considered to control the charging pressure. As a controller-internal model a piecewise-affine model is generated by means of system identification using measurement data. For the prediction model in the linear MPC in every time-step the recent linear model out of the piecewise-affine model is used. It is shown that the controller can adjust the wastegates for the two stages to appropriately track the charging pressure. The control quality is only impaired for large load steps. In these case overshoots occur which do not fulfill the criteria on control quality. Ref. [17] describes the use of a physical model for two stage turbocharging. In this work the the physical model is used within a NMPC based on multiple-shooting. As architecture also the control of the charging pressure by use of LP and HP wastegates is considered. The concept is validated with experiments, where the functionality is approved. Even for large load steps the high requirements on control quality can be fulfilled.

3.2.3 *Summary*

All in all it shows that the application of MPC for airpath technology on gasoline engines is quite mature. The literature offers a quite broad range of physical models which can be applied for the purpose of real-time feasible MPC. Linear-time invariant concepts do not seem to tackle the challenges with airpath control. However, the use of more complex MPC schemes, such as the use of different linear models at different operating points or even nonlinear MPC do seem to fulfill all arising requirements on control quality. Future research should concentrate on more sophisticated architectures which arise by combination of variable valve train, several EGR-loops and several turbocharges. Additionally, concepts such as the combination of turbocharging and EGR need further real-world validation.

4 Numerical case study: two stage turbocharging for gasoline engines

Typical setups for turbocharging in a gasoline engine are depicted in Figure 1. In case of a single stage gasoline turbocharging concept, a throttle is combined with a HP turbocharger. This concept leads to a trade-off between high specific power and a fast transient raise of the charging pressure. Especially the dimensioning of the turbocharger has influence on these two criteria. The use of additional variability in the airpath can mitigate this trade-off. In this context two stage turbochargers are investigated. The two stage turbocharging concept is characterized by an additional LP turbocharger. This allows to use the HP stage for realizing fast transient raise due to its small dimensions. In contrast to that the LP stage realizes high specific power with slow transient dynamics due to its large dimensions.

For actuation of the turbocharger in a gasoline engine typically wastegates are used. The application of variable turbine geometry can usually not be realized in a cost effective manner due to the hot exhaust gas temperatures. The hot exhaust gases also prevent the use of sensors in the exhaust path in a series production setup, such as temperature or pressure sensors. The wastegates and the throttle together are used to adjust the intake manifold pressure which is the controlled variable of the system and usually measured by a pressure sensor. For reasons of fuel efficiency, the throttle is not used in the charged operating range. As consequence the task of the throttle is to control the intake manifold pressure when the desired pressure is smaller than the ground charging pressure. The ground charging pressure is the pressure which results when the wastegate is entirely open and is a bit higher than the atmospheric pressure. In the charged region the wastegates are used for appropriate intake manifold pressure control and the throttle valve is entirely open, such that the charging pressure can be assumed to be the same as the intake manifold pressure.

The requirements for the closed-loop control quality of the charging pressure in a single stage turbocharger are typically the following [15]:

- Max. over- and undershoot for small load step: 50 mbar;
- Max. over- and undershoot for big load step: 150 mbar;
- Max. tracking error during a ramp-type signal: 150 mbar;
- Max. steady state error: 2%;
- Max. turbocharger speed.

In case of two stage turbocharging, the closed-loop controller has to coordinate both turbocharger stages, while considering the above mentioned requirements. In the following it is shown that a NMPC

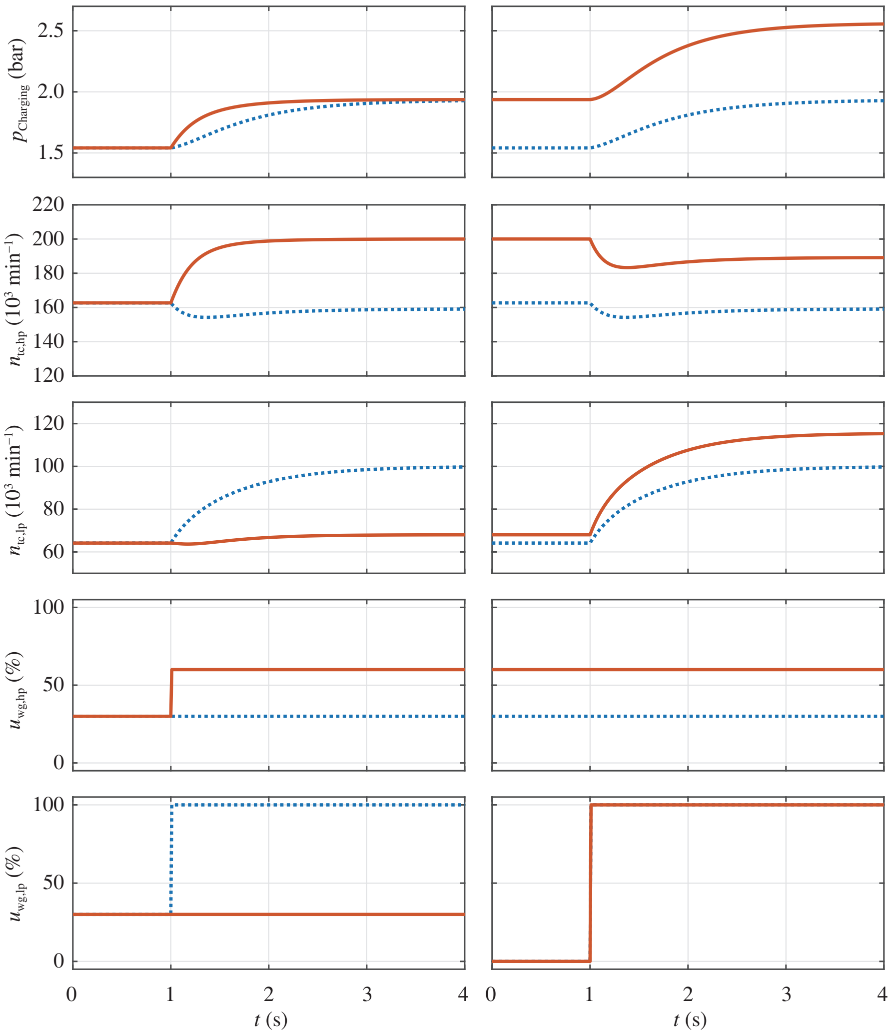

Figure 2 (Color online) Dynamic system behavior of charging pressure p_{Charging} and turbocharger speeds n_{tc}. Left: Step in high-pressure wastegate $u_{\text{wg,hp}}$ (solid red) vs. step in low-pressure wastegate $u_{\text{wg,lp}}$ (dashed blue). Right: low-pressure wastegate step for constant $u_{\text{wg,hp}} = 30\%$ and $u_{\text{wg,hp}} = 60\%$.

based controller is able to almost entirely realize the more strict requirements of a single stage turbocharger. The focus is put on showing the advantages and possibilities of NMPC rather than demonstrating the details of the NMPC controller. For this purpose closed-loop simulations are conducted with different settings. The simulation model and the NMPC controller are based on the work in [18], only parameter settings have been changed.

4.1 Turbocharger system dynamics

In general the turbocharger has a significant dynamic behavior with time constants in the order of seconds which results in the so called turbo lag. In case of the two stage turbocharging setup, the time constants are different for the two stages which has to be accounted for in the control algorithm. With respect to controller design, the nonlinearity of the system dynamics has to be also considered. One of the arising effects is the strong coupling of the inputs. The actuation of one input influences the behavior of the other input. This behavior is shown in Figure 2. The figure shows the step response with the arising time constants of the HP and the LP stage. It takes much longer time to achieve the same pressure level for the LP stage ($t_{95} = 1.8$ s) in comparison to the HP stage ($t_{95} = 0.9$ s). In the right part of the figure the nonlinearity and the coupling of the input is demonstrated. The LP stage makes a step from 0% (fully open) to 100% (fully close). This maneuver is conducted once with HP wastegate actuation of 30% and once with 60% (each time the actuation is constant). It results a change in charging pressure for steady state conditions in 0.62 bar compared to 0.38 bar. The physical reasoning is that the change of the HP wastegate actuation changes the input conditions at the LP stage which influences the operating point. This behavior can be seen especially in the LP turbocharger speeds which depend on HP actuation.

4.2 Simulative validation of the controller

The above mentioned system dynamics and requirements on control are prime examples for the scope of application of NMPC. The NMPC is able to consider the multiple inputs with strong coupling of the inputs as well as the nonlinearity. Due to the prediction based control also the different time constants can be directly compensated for. At the same time the optimization based control can take care of the turbocharger speed limits. For fully exploiting the capabilities of the system, the HP stage should be used to quickly increase pressure in transients. However, only as much as possible do not exceed the speed limits. The LP stage should be used to realize high pressure levels in stationary conditions. As consequence, the NMPC should exploit the capabilities of the system by appropriate prediction of the system behavior.

To calculate an optimal control sequence the NMPC algorithm conducts an optimization in every sampling time. The optimization minimizes a cost function which determines the objectives and along with that the behavior of the controller. In case of the two stage turbocharging, a possible cost function reads as

$$\min_{\boldsymbol{x}(\cdot),\, \boldsymbol{u}(\cdot)} \quad \int_0^{t_{\mathrm{ch}}} F\left(\boldsymbol{x}(t), \boldsymbol{u}(t)\right) \mathrm{d}t + F_N\left(\boldsymbol{x}(t_{\mathrm{ch}})\right) \tag{1}$$

$$\begin{aligned} \text{s.t.} \qquad & 0 = \boldsymbol{x}(0) - \bar{\boldsymbol{x}}_0, && (2)\\ & 0 = f(\dot{\boldsymbol{x}}(t), \boldsymbol{x}(t), \boldsymbol{z}(t), \boldsymbol{u}(t)), \quad \forall t \in [0, t_{\mathrm{ch}}]. && (3) \end{aligned}$$

This cost function is minimized under consideration of the following path bounds:

$$\begin{aligned} & \underline{n}_{\mathrm{tc,hp}} \leqslant n_{\mathrm{tc,hp}}(t) \leqslant \bar{n}_{\mathrm{tc,hp}}, \quad \forall t \in [0, t_{\mathrm{ch}}], && (4)\\ & \underline{n}_{\mathrm{tc,lp}} \leqslant n_{\mathrm{tc,lp}}(t) \leqslant \bar{n}_{\mathrm{tc,lp}}, \quad \forall t \in [0, t_{\mathrm{ch}}], && (5)\\ & \underline{u}_{\mathrm{wg,lp}} \leqslant u_{\mathrm{wg,lp}}(t) \leqslant \bar{u}_{\mathrm{wg,lp}}, \quad \forall t \in [0, t_{\mathrm{ch}}], && (6)\\ & \underline{u}_{\mathrm{wg,hp}} \leqslant u_{\mathrm{wg,hp}}(t) \leqslant \bar{u}_{\mathrm{wg,hp}}, \quad \forall t \in [0, t_{\mathrm{ch}}]. && (7) \end{aligned}$$

The stage and final cost functions are defined as

$$\begin{aligned} F\left(\boldsymbol{x}(t), \boldsymbol{u}(t)\right) &= \|p_{\mathrm{Charging}}(t) - p_{\mathrm{Charging,ref}}(t)\|_Q^2 + \|\dot{\boldsymbol{u}}(t)\|_{\boldsymbol{R}}^2, && (8)\\ F_N\left(\boldsymbol{x}(t_{\mathrm{ch}})\right) &= \|p_{\mathrm{Charging}}(t_{\mathrm{ch}}) - p_{\mathrm{Charging,ref}}(t_{\mathrm{ch}})\|_{Q_N}^2. && (9) \end{aligned}$$

$\boldsymbol{x}(t) \in \mathcal{R}^{n_x}$ denotes the differential states, $\dot{\boldsymbol{x}}(t)$ the differential state derivatives, $\boldsymbol{z}(t) \in \mathcal{R}^{n_z}$ the algebraic variables and $\boldsymbol{u}(t) \in \mathcal{R}^{n_u}$ are the control inputs and $\dot{\boldsymbol{u}}(t)$ their derivatives. The optimization problem depends on the current state estimate $\bar{\boldsymbol{x}}_0 \in \mathcal{R}^{n_x}$, within the initial value condition of (2). The nonlinear dynamics of the airpath system are given by a Differential-Algebraic-Equation system which enter the OCP in (3). The details on the numerical implementation of the optimization algorithm and the controller internal model can be found in [18].

The cost function is designed to fulfill the specifications on the closed-loop system. For this reason a least squares tracking cost for tracking of the charging pressure is introduced, which handles the reference tracking. Additionally the derivates of the control inputs are introduced in (8). This term reduces the sensitivity of the actuated signals to measurement noise. The path constraints consist of the simple bounds on the actuated values and on the turbocharger speed limits (4) to (7).

In the following it is shown in simulation that the high requirements on control quality can be fulfilled and that the controller can be easily parametrized to account for a different control behavior. The left

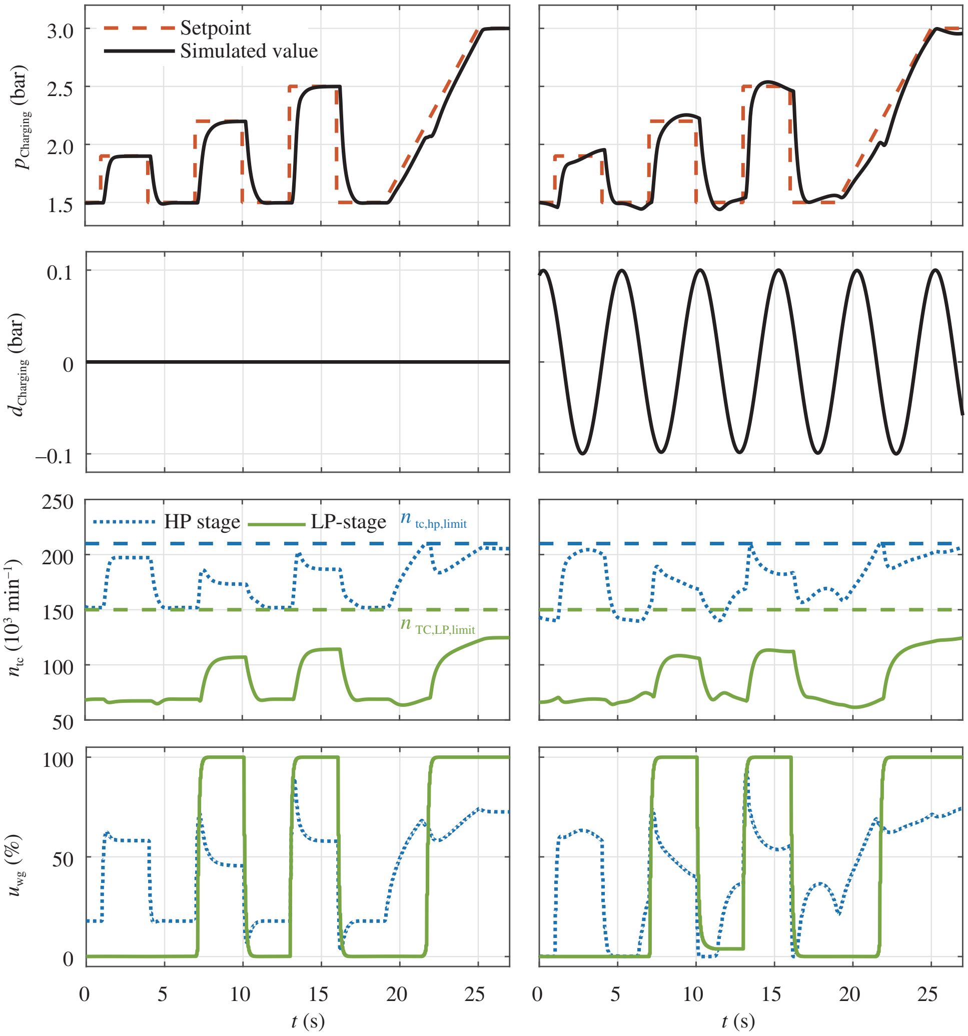

Figure 3 (Color online) Closed-loop control result of charging pressure p_{Charging} along with resulting turbocharger speed n_{tc} and actuated signal u_{wg}. Left: nominal NMPC controller. Right: nominal NMPC controller with sinusoidal output disturbance d_{Charging}.

part of Figure 3 shows a control result of the closed-loop system (CLS). Several steps in the reference signal and a ramp-like reference signal are applied. The NMPC controller is able to appropriately conduct reference tracking: neither a steady-state error nor overshoot is present. Additionally the controller is able to use the HP stage, without overstepping the limits of the HP-turbocharger speed. This behavior allows for optimal exploitation of the two stage turbocharging system. The right part of Figure 3 shows additionally the behavior if an output disturbance is present. In this case a sinusoidal output disturbance was added with amplitude of 100 mbar which is a reasonable value for the model-plant mismatch. The simulation shows that the controller can still handle this situation, and no excessive errors occur.

The calibration parameters of the NMPC controller can be separated into three categories: model parameters, parameters for numerical optimization and parameters for control tuning. It is usually not possible to build-up a process model which is entirely based on fundamental equations with physically known quantities. Usually some of the parameters (even if they are physical) have to be estimated as they are not (directly) measurable such as an valve discharging coefficient. Additionally often some parts of the model are black-box models which are based on input/output measurements. In these cases calibration parameters have to be determined. However, the big advantage is that the suitability of the calibration parameters can directly be determined by comparing simulation data to measurement data. In the second category, there are the parameters for numerical optimization. These have to be set such

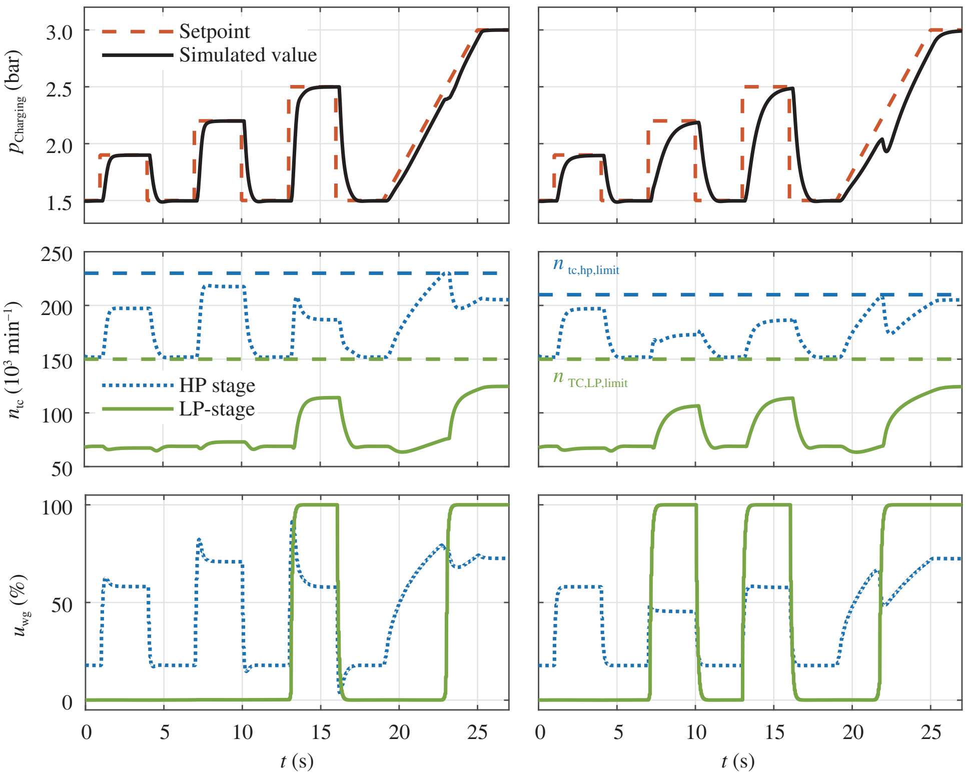

Figure 4 (Color online) Closed-loop control result. Left: change of HP-turbocharger speed limit in NMPC. Right: less aggressive control via change of weighting matrices.

that a solution of the optimization problem can be found in a robust manner, such as the step length for the line search. They can also be evaluated, e.g., by checking the KKT tolerance. In the third category there are the parameters for tuning the control behavior. These are the parameters which are present in the cost function, namely the control horizon and the weighting factors. Consequently, only very few parameters are left for influencing the control behavior.

The next two simulations show the possibility to easily parametrize the controller. The left part of Figure 4 shows the CLS result, if the turbocharger speed limit is changed to 230.000 1/min from originally 210.000 1/min in nominal operation (as shown in Figure 3). All remaining NMPC parameters are the same as in the nominal case, thus only one parameter is changed. One can see that the little change in control specification has a significant change in the control behavior. Now, the second step in the reference signal can be entirely realized with the HP stage only. Due to the predictive behavior the NMPC is aware of that. To account for this, no recalibration has to be conducted other than the one number for the speed limit. As second case the nominal controller is compared to a controller which is less aggressive. For this purpose the weighting parameter Q has to be changed. In the right part of Figure 4 the CLS result is shown with a weighting parameter that is 70 times smaller than the one used in the nominal operation $70Q_{\mathrm{smooth}} = Q_{\mathrm{nominal}}$. In the CLS result, the actuated signals are changed with lower bandwidth and thus also the reference tracking gets slower. As result, in transients the HP turbocharger speed is far away from the speed limit.

All in all, the numerical case study shows that for a complex system, such as the two stage turbocharging, NMPC offers many benefits. It can achieve high control performance, despite the coupled multiple-inputs with nonlinear system dynamics. Additionally in- and output limits can be enforced which is crucial for this system. At the same time, the parametrization of the cost function gets very intuitive. Specifications on the CLS, such as limits on the turbocharger speed, can directly be correlated to changes in the cost function.

5 Conclusion

Model predictive control is an advanced control technology offering various advantages. The MPC algorithm can systematically handle (nonlinear) MIMO system dynamics while respecting constraints on actuated and controlled signals. These benefits make MPC very interesting for the application in engine control. In engine control the amount of sensors and actuators and along with that the number of control loops are constantly increasing. As consequence the calibration of the control algorithms becomes a major challenge. In this paper the benefits of using MPC is exemplified for gasoline two stage turbocharging control. The possibility to drastically reduce calibration time is shown by closed-loop simulations. It is shown how different specifications on the closed-loop control can be realized by simple changes of parameters in the cost function of the MPC algorithm, such as different limits on turbocharger speeds. The topic of exhaust gas recirculation control will be very interesting and relevant for future high efficiency gasoline engines which might be tackled by MPC.

Acknowledgements This research was performed as part of the Research Unit (Forschergruppe) FOR 2401 “Optimization based Multiscale Control for Low Temperature Combustion Engines” which is funded by the German Research Association (Deutsche Forschungsgemeinschaft, DFG). The support is gratefully acknowledged.

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