Control Engineering Practice 19 (2011) 287–297

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Modeling and control of the air system of a turbocharged gasoline engine

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ARTICLE INFO

Article history:
Received 7 November 2008
Accepted 11 November 2009
Available online 29 December 2009

Keywords:
Engine control
Trajectory generation
Turbocharger
Engine modeling
Anti-wind up
Flatness based control

ABSTRACT

In order to reduce CO_2 emissions in the automotive industry, there is a trend to decrease the size of the engines and add turbocharging technologies to increase the engine efficiency while keeping performances. In this context, numerous studies have focused on the improvement of turbocharger control strategies. The strategy proposed in this paper is based on constrained motion planning and feedback linearization applied to a simplified model of the system. It takes advantage of the whole system bandwidth and requires a limited calibration effort. Thanks to its structure, it offers an interesting potential for generalization to more complex turbocharging systems. Extensive experimental tests are reported for a four-cylinder gasoline engine.

1. Introduction

1.1. Motivation

In the automotive industry, there is a trend to decrease the size of the engines cylinders in order to improve their combustion efficiency (reduction of friction and pumping losses) and hence decrease the CO_2 emissions. Turbocharging devices compensate for the consequent torque reduction. This technique, called downsizing, has been detailed in various publications (see for example Lake, Stokes, Murphy, Osborne, & Schamel, 2004; Leduc, Dunbar, Ranini, & Monnier, 2003; Petitjean, Bernardini, Middlemass, & Shahed, 2004). Since turbochargers are a key element in this technology, many works focus on the design of new control strategies for this system.

This paper describes the development of a turbocharger control strategy consisting of constrained motion planning and feedback linearization applied to a reduced dynamic model. It concentrates on single stage fixed geometry turbochargers because this system remains simple and is therefore a good starting point to develop a new strategy. But its solution can be generalized to more complex applications. The reduced model takes account of the interactions between the turbocharger and its environment, and it provides both steady state and dynamic feedforward action with the consideration of actuator constraints. As a consequence a limited calibration effort is required.

The article is organized in five sections. Section 1 introduces the work by presenting the system studied, the objectives of turbocharger control strategies and the contributions of this paper. Section 2 describes a model of the system appropriate for the design of a model based control strategy, and analyzes its properties. In particular, the exponential stability of the system around any feasible trajectory is demonstrated. Then, in Section 3, a trajectory satisfying the actuator constraints is designed to provide a feasible setpoint, leading to the proposition of a feed forward strategy. A robustness study underlines the need for a feedback control strategy in order to compensate for model errors. This feedback is detailed in Section 4. Finally, Section 5 shows extensive experimental results of the proposed strategy.

1.2. System description

The engine considered in this paper is a four cylinder turbocharged gasoline engine shown in Fig. 1. Fresh air enters in the engine through the compressor which increases the air density. The air is burnt in the cylinder where the combustion results in the production of mechanical torque. At the exhaust of the system, the turbine converts part of the gas enthalpy into mechanical power on the turbocharger shaft, whose dynamics are the consequence of the balance between the compressor and turbine powers.

Two actuators are available on the air system. The wastegate diverts part of the exhaust gas from the turbine, resulting in a change of the energy provided to the turbocharger shaft. The intake throttle acts on the intake manifold pressure by creating a pressure drop downstream from the compressor and heat exchanger.

The turbocharger has a direct influence on compression and expansion ratios, and on temperatures downstream from the

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doi:10.1016/j.conengprac.2009.11.006

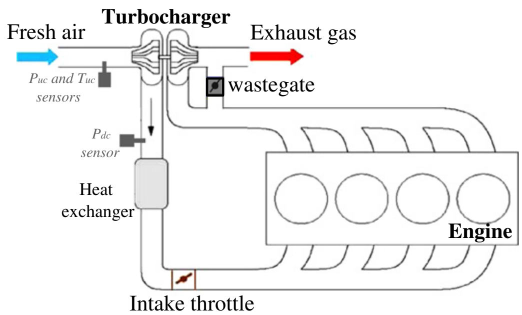

Fig. 1. Engine diagram. The actuator is the wastegate, the measurements are the compressor upstream temperature and pressure and the downstream pressure.

compressor and the turbine. Its behavior, however, depends on variables related to other components, including: engine speed, atmospheric pressure, ambient temperature, exhaust manifold temperature and pressure downstream turbine. In this paper these variables are referred to as environmental variables or conditions. They can be measured or estimated easily (see appendix for further details on how these variables are taken into account in the control oriented model designed in this paper, and see Eriksson, 2002 for exhaust models or Eriksson et al., 2002 for pressure drops models).

The following measurements are available on the system:

- Engine speed N_e.
- Compressor downstream pressure P_{dc}.
- Compressor upstream pressure and temperature P_{uc} and T_{uc}.

1.3. Control objectives

The main objective of the engine control strategies is to provide a required mechanical torque on the engine shaft (see for example Guzzella & Onder, 2004 for details). On a gasoline engine running at stoichiometry (due to pollutant emission constraints), this torque is directly linked to the air mass aspirated by the cylinder which depends on the intake manifold air density. The goal of air path management is therefore to control the intake manifold pressure P_{man}^{sp}. The intake throttle allows fast direct action on this variable, but is constrained by its upstream pressure at the compressor outlet. Since energy losses are minimized when the throttle is open, the aim of the turbocharger control strategy is to respect a compressor downstream pressure setpoint $P_{dc}^{sp} = P_{man}^{sp}$ via actuation of the wastegate. This objective must be followed while considering two constraints. The turbocharger speed must be maintained below a maximum value for safety reasons, and the actuator is mechanically constrained between extremal values (fully open and closed).

Throttle and turbocharger controls are active simultaneously. However, good tracking of the compressor downstream pressure setpoint will ensure that the throttle is fully open in the turbocharging operating zone. On the contrary, a throttle closure will compensate for overshoots on compressor downstream pressure. In this paper, the throttle and wastegate control are considered independently and only the wastegate control will be discussed. However, when analyzing the experimental results (in Section 5) it is important to verify that the overshoots of the turbocharger control strategy do not generate any action on the throttle. A description of the throttle control strategy used in this application can be found for example in Leroy, Chauvin, and Petit (2009).

As a summary, the control problem addressed is a fast transition problem for a single input single output nonlinear system, with constraints on the state and on the input. The control input is the normalized wastegate effective area (u ranging from 0 to 1) and the state (and the output) is the pressure downstream from the compressor P_{dc}.

1.4. Turbocharger control

Different approaches have been proposed concerning control issues involving turbochargers. Most of the works published on this topic describe the conventional strategies, used on commercial cars, as consisting of a linear controller with gain scheduling and feed forward terms given by steady state maps (see Daubler, Bessai, & Predelli, 2007; Ortner & del Re, 2007; Schwarzmann, Nitsche, & Lunze, 2006).

The drawbacks of these basic controllers are linked to the application of linear control techniques to nonlinear systems: the compromise obtained between performance and robustness is not satisfying on the whole operating range of the system. Moreover, the calibration task is heavy as controller parameters, feedforward maps and corrections have to be tuned on each operating point.

A large number of control techniques has been tried, ranging from model based gain scheduling (Daubler et al., 2007), to sliding mode control (Ouenou-Gamo, Rachid, & Ouladsine, 1997), predictive control (Colin, Chamaillard, Bloch, & Charlet, 2007; Colin, Chamaillard, Bloch, & Corde, 2007; Ortner & del Re, 2007), H^∞ control (Jung, Glover, & Christen, 2005; Wei & del Re, 2007). Nevertheless, those works are based on linearized versions of the modeling of the system. Again, a lot of calibration is needed in order to get a good trade-off between performance and robustness.

Based on this observation, improvements were proposed based on models of the system, either by using identification techniques (see Colin, Chamaillard, Bloch, & Charlet, 2007; Colin, Chamaillard, Bloch, & Corde, 2007; Wei & del Re, 2007), or a physical representation of the system (see Daubler et al., 2007; Karnik, Buckland, & Freundenberg, 2005; Muller, 2008; Ortner & del Re, 2007; Schwarzmann et al., 2006) which is more interesting when considering the variation in operating conditions such as atmospheric pressure.

1.5. Contributions of the paper

The strategy proposed in this paper is based on constrained motion planning and feedback linearization applied to a simplified model. In this combination, each element is important and will be detailed. In a first step, following Moulin, Chauvin, and Youssef (2008), a control oriented model is developed. The model reduction keeps the main dynamics governing the behavior of turbochargers and the dependencies on environmental conditions. Then, a model based control strategy is presented, taking into account actuator constraints and integrator anti-windup.

The contributions and the novelty of the proposed approach are as follows:

- The structure of the model provides steady state and dynamic feedforward action taking account of actuator constraints, with a limited calibration effort. It also naturally adapts to varying environmental conditions and can therefore be generalized to more complex applications.
- As a consequence, the feedback action is also kept very simple and therefore easy to calibrate. It requires only three gains kept constant over the overall operating range. Other control strategies can have performances relatively close to that presented, but at the price of considerable calibration effort. The results of the study demonstrate that constrained motion