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Nonlinear internal model controller design for wastegate control of a turbocharged gasoline engine[☆]

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ABSTRACT

Internal Model Control (IMC) has a great appeal for automotive powertrain control in reducing the control design and calibration effort. Motivated by its success in several automotive applications, this work investigates the design of nonlinear IMC for wastegate control of a turbocharged gasoline engine. The IMC design for linear time-invariant (LTI) systems is extended to nonlinear systems. To leverage the available tools for LTI IMC design, the quasi-linear parameter-varying (quasi-LPV) models are explored. IMC design through transfer function inverse of the quasi-LPV model is ruled out due to parameter variability. A new approach for nonlinear inversion, referred to as the structured quasi-LPV model inverse, is developed and validated. A fourth-order nonlinear model which sufficiently describes the dynamic behavior of the turbocharged engine is used as the design model in the IMC structure. The controller based on structured quasi-LPV model inverse is designed to achieve boost-pressure tracking. Finally, simulations on a validated high-fidelity model are carried out to show the feasibility of the proposed IMC. Its closed-loop performances are compared with a well-tuned PI controller with extensive feedforward and anti-windup built in. Robustness of the nonlinear IMC design is analyzed using simulations.

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1. Introduction

Internal Model Control (IMC), whose diagram is shown in Fig. 1, is a well-established control design methodology with an intuitive control structure (Morari & Zafiriou, 1989). It incorporates a system model as an explicit element in the controller so that the control actions are determined based on the difference between the model output and the plant output. It has several desired features and closed-loop properties as established in Morari and Zafiriou (1989) and Garcia and Morari (1982), such as dual stability criterion, zero offset, and perfect control. The design, analysis, and implementation of IMC for linear systems have been well developed. Rivera, Morari, and Skogestad (1986) showed that process industrial IMCs for many SISO models can lead to PID controllers, occasionally augmented with a first-order lag. They also demonstrated the superiority of using IMC for PID tuning in terms of closed-loop performance and robustness.

The efficacy of IMC for nonlinear systems, however, has been investigated with limited comprehensive results. Economou, Morari, and Palsson (1986) presented an important result of nonlinear IMC, proving that the dual stability criterion, zero offset, and perfect control properties of LTI IMC would carry over to nonlinear cases. The IMC was implemented by finding a nonlinear dynamic inverse, which remained to be the key challenge in extending the IMC design to nonlinear systems. While the invertibility condition, inverse structure, and derivation for nonlinear dynamic system inverse were studied (Hirschorn, 1979), the derivation of the nonlinear inverse involved higher-order derivatives and caused problems when noises and disturbances were present in the system. In Economou et al. (1986), the nonlinear inverse was derived by exploiting the Hirschorn nonlinear inverse structure and solving it numerically using the contraction principle method or Newton's method. Stability of the IMC structure was discussed under the ideal circumstance that the model was the same as the plant. Henson and Seborg (1991) also exploited the result of Hirschorn nonlinear inverse for nonlinear IMC design. Several assumptions were made to calculate the higher-order derivatives. Feedforward/feedback linearization approach was adopted by Calvet and Arkun (1988) to derive the model for the nonlinear

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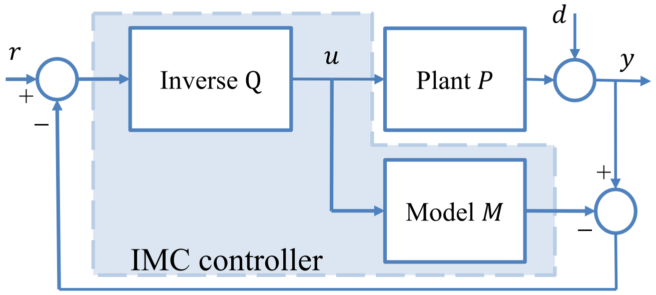

Fig. 1. Internal model control structure.

plant in IMC. Their approach accounted for the disturbances and input constraints.

Nonlinear IMC was also investigated in the adaptive control framework. Hunt and Sbarbaro (1991) used artificial neural networks for adaptive control of nonlinear IMC. Feasibility of identifying the nonlinear model and its inverse by a neural network was explored and demonstrated. Boukezzoula, Galichet, and Foulloy (2000) and Xie and Rad (2000) used fuzzy logic to estimate the model dynamics. The inverse was derived from this fuzzy model. The black-box identifications of neural network and fuzzy logic made it difficult to incorporate physical knowledge about the plant in the IMC design. In adaptive IMC scheme, using linear models to represent the dynamics of the nonlinear plant though adaptation has also been exploited (Brown, Lightbody, & Irwin, 1997; Datta, 1998; Shafiq, 2005).

Another possible avenue to exploit the linear IMC design tools for nonlinear systems would be through the linear parameter varying (LPV) model. Mohammapour, Sun, Karnik, and Jankovic (2013) applied IMC on a quasi-LPV model with two approaches. In the first approach, the IMC controller parameters were scheduled based on the LPV model parameters which were assumed to be known in real time and not vary rapidly. In the second approach, the design problem was formulated in the H_∞ framework as a set of linear matrix inequalities (LMI). Solving the associated LMI problem, however, was computationally intensive. Toivonen, Sandström, and Nyström (2003) derived the LPV model based on velocity-based linearization, then developed the IMC controller based on linear IMC theory. It was much less computationally demanding, but it was only applicable when there were a small number of scheduling parameters.

This paper explores nonlinear IMC for turbocharged gasoline engines driven by the need for developing robust and easy-to-calibrate powertrain control solutions and motivated by several successful industrial applications. IMC was first applied to turbocharged diesel engines for automotive applications. Alfieri, Amstutz, and Guzzella (2009) applied IMC based on the classical Smith predictor structure to air–fuel ratio control in turbocharged diesel engines with exhaust gas recirculation. Schwarzmann, Nitsche, and Lunze (2006) treated boost-pressure control of a turbocharged diesel engine with a variable nozzle turbine with IMC. Their IMC utilized a flatness-based approach to design the inverse Q, in which flatness means that the system inputs can be explicitly expressed in terms of internal system dynamics. In a follow up work, the same group also dealt with a two-staged turbocharged diesel engine using IMC (Schwarzmann, Nitsche, Lunze, & Schanz, 2006). The inverse Q was designed based on geometric nonlinear control design method. As turbocharged gasoline engines are becoming more popular, advanced control designs including IMC have been applied to turbocharged gasoline engines for improved performance. Thomasson, Eriksson, Leufven, and Andersson (2009) utilized IMC for PID tuning of wastegate control in turbocharged gasoline engines. Karnik and Jankovic (2012) later applied IMC directly to wastegate control for a turbocharged gasoline engine, motivated by the successful applications on turbocharged diesel engines. They used a first-order model which was simplified from a fourth-order nonlinear model using singular perturbation. While the simplicity of the first-order model-based design was an advantage for implementation, its performance was limited by the linear approximation, as it is defined for a particular operating point.

This work investigates the feasibility, performance, advantages, and limitations of a nonlinear IMC for automotive powertrain-control design, using the fixed geometry turbocharged gasoline engine as a case study. While the nonlinear dynamics of the system can be sufficiently described by a fourth-order model, inverting the nonlinear model for the IMC design represents the major challenge. To facilitate the IMC design, a quasi-LPV model (Rugh & Shamma, 2000) for the nonlinear model is developed. More importantly, the special quasi-LPV model structure is explored, and a structured quasi-LPV model is proposed, which leads to a feasible nonlinear inverse, referred to as the structured quasi-LPV inverse. The IMC based on the structured quasi-LPV inverse is developed, and its performance is analyzed. Simulation results, using a validated “virtual” plant model, are presented to demonstrate the effectiveness of the proposed design. This work is applicable to IMC with SISO nonlinear models of higher-order and is not limited by the number of scheduling parameters. The proposed IMC was originally presented as a conference paper (Qiu, Sun, Jankovic, & Santillo, 2014), whereas this paper represents an expanded version. More specifically, the design procedure is discussed in more detail from the stability point of view and robustness analysis is included.

The paper is organized as follows: Section 2 states the problem, presents two main tools used: IMC and LPV. Section 3 presents the nonlinear model for the turbocharged gasoline engine and exploits quasi-LPV approach to derive its inverse. Section 4 analyzes the IMC implementation results. Section 5 summarizes the paper.

2. Control problem and preliminaries

Gasoline engines have been aggressively downsized in an effort to reduce fuel consumption and CO_2 emissions. However, the torque provided by the engine is proportional to the air delivered to the cylinders. To meet the consumer demands for performance on the downsized engines, i.e., to maintain the engine output torque, turbochargers are widely adopted. They compress the intake air to increase the density of the engine airflow, thereby increasing the torque. The schematic of a turbocharged gasoline engine is shown in Fig. 2. The wastegate is the main actuator to control boost pressure. It affects the engine operation by changing the rotational speed of the turbine/compressor. The air is compressed by the compressor, and passes through an intercooler and a throttle before entering the engine intake port. The engine exhaust port is connected to the turbine, which is mechanically connected to the compressor. An electric wastegate actuator controls the opening of the turbine bypass path in this application (Karnik & Jankovic, 2012), affecting the compressor speed and therefore the boost pressure.

The turbocharged gasoline engine is expected to produce the desired engine torque, with higher fuel efficiency, power density, and lower emission (Guzzella & Onder, 2010). To achieve such goal, the desired engine torque is calculated from the driver pedal position. The desired engine torque is then mapped into desired intake manifold pressure and boost pressure considering the fuel economy and emission. These two pressures are then tracked through throttle and wastegate. This two input two output control problem can often be tackled with a decentralized controller:

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