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An Application of Reference Governor to a Diesel Engine Air Path System: Implementation of a Multi-Variable Reference Modification Algorithm

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Abstract: This paper considers an application of a reference governor (RG) to the air path system of an automotive diesel engine. The air path system can be represented as a multi-input-multi-output (MIMO) nonlinear system which has hardware interaction between fresh air and exhaust gas paths resulting from a turbocharger and an exhaust gas recirculation (EGR). The system has several constraints which should be considered in control design, such as maximal boost pressure, turbine speed and EGR min-max constraints. In order to explicitly deal with the constraints, we employ an online RG to modify boost pressure and the EGR rate references so that their predicted values ensure the constraints. Using a prediction model obtained via system identification the RG algorithm is established based on a planar search combined with the gradient descent method and a bisectional search. An experimental result using a real engine is shown to demonstrate the effectiveness of the present method.

Keywords: Diesel engine air path, reference governor, gradient descent method.

1. INTRODUCTION

In real-world control systems, there are a lot of constraints to be considered in the control design, which stem from hardware and control limits. For example, air path systems of automotive diesel engines contain several constraints such as maximal limits on boost pressure, exhaust manifold pressure and turbine rotation speed. Most of the air path systems have exhaust gas recirculation (EGR) path to feed exhaust gas into the intake manifold to reduce nitrogen oxides (NO_x). The EGR rate has minimal and maximal constraints. Namely, if the EGR rate is too low, a desirable NO_x reduction would not be achieved. With a high EGR rate in the intake manifold, combustion instability could happen. In addition, actuator limits usually exist in real-world control systems. If such a constraint is discarded in the control design and the plant is regarded as a linear system, it is well-known that this could cause undesirable behavior such as a wind-up phenomenon, in the worst case, which could lead to instability (Gilbert, 1992).

One of control methods that can explicitly treat constraints is a reference governor (RG) (Bemporad, 1998; Gilbert and Kolmanovsky, 2002; Hatanaka et al., 2007; Hirata and Fujita, 1999; Kogiso and Hirata, 2003; Kolmanovsky et al., 1997, 2014). It computes a modified reference such that predicted variables satisfy constraints in a prescribed prediction horizon. There are two merits in applying the RG to the air path systems.

(i) By introducing such a control method that can directly deal with constraints, tracking performance near constraints could be improved to meet emission regulation that is becoming more stringent year by year.
(ii) An existing feedback controller that had been developed can be combined with the RG.

Among preceding research works related to RG, there were several application studies reported such as the applications to a stand-alone generator (Elder et al., 1985), a control of micro hydroelectric generation (Henderson, 1998), a fuel cell (Vahidi et al., 2007), a helicopter (Kogiso and Hirata, 2003), a torque control for a turbocharged diesel engine (Kolmanovsky et al., 1997), a high pressure steam condenser (Hatanaka et al., 2007) and a load control in multi-cylinder recompression HCCI engines (Jade et al., 2014). In Nakada et al. (2012, 2014), two application results of RG to diesel engine control were presented. The one was catalyst temperature control (Nakada et al., 2012), and the other was a boost pressure control (Nakada et al., 2014). The RG algorithms in the papers were based on a bisectional search or a gradient descent method. However, both applications considered the modification of only a single reference rather than multiple references. At this moment, there is no preceding application works that deal with multiple references. In order to extend the

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applicability of RG to more complex real-world control systems, it is necessary to study the extension of the RG to systems with multiple references.

In this paper, we consider an RG for constrained systems with multiple references and its application to a diesel engine air path system. The control of the air path system is a typical problem to handle a multi-input-multi-output (MIMO) system with multiple references and multiple constraints. We propose an online RG algorithm that modifies two references of the boost pressure and the EGR rate at the same time under constraints on boost pressure, exhaust manifold pressure, turbine speed and the EGR rate. The algorithm is based on a gradient descent method and a bisectional search to optimize an objective function in a planar space. The effectiveness and the applicability of the present method to real-world control systems will be demonstrated by an experiment using a real vehicle with a diesel engine.

2. SYSTEM CONFIGURATION

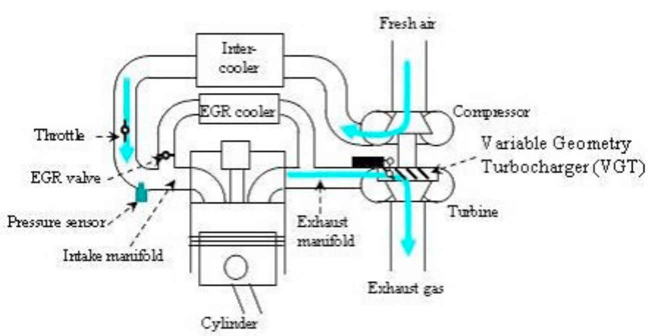

Fig. 1. The air path system of a diesel engine

We consider an air path system of a diesel engine shown in Fig. 1. This system has a variable geometry turbocharger (VGT) composed of a compressor in the intake path, a turbine in the exhaust path and a turbine shaft connecting between them. By changing the position of vanes attached to the turbine, we can change both the exhaust gas mass flow through the turbine and the energy transferred from the turbine to the compressor through the turbine shaft. As a result, the intake manifold pressure called the boost pressure can be indirectly controlled via the vane position. A boost pressure sensor is located at the intake manifold.

Between the exhaust manifold and the intake manifold, there is an exhaust gas recirculation (EGR) path. A part of the exhaust gas can be introduced through the EGR path into the intake manifold to make the oxygen density in cylinders lower than the no-EGR case. This results in the reduction of nitrogen oxide (NO_x) in the emission. On the other hand, excessive EGR could cause the increase of particulate matter (PM). Therefore, in order to compromise between the amounts of NO_x and PM, we need to control the EGR rate precisely using an EGR valve and a throttle as actuators.

An intercooler is located downstream of the compressor, with an EGR cooler located upstream of the EGR valve. The intercooler can reduce the temperature of the compressed fresh air and increase its density, resulting in an increase of the amount of the fresh air flowing into the cylinders to generate more engine torque. The EGR cooler protects the EGR valve from heat coming from the exhaust gas by lowering its temperature.

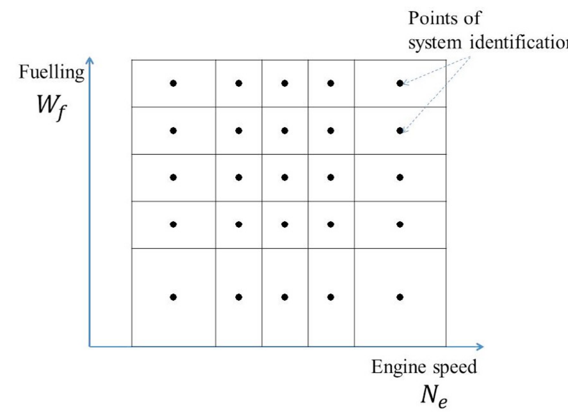

Fig. 2. A partition of operating regions

In this paper, we consider the tracking control of both the EGR rate $F_{im} \in \mathbb{R}$ and the boost pressure $p_{im} \in \mathbb{R}$ in the intake manifold. We can use three actuators as control inputs, namely, a throttle position $u_{th} \in [0, 100]$, an EGR valve position $u_{egr} \in [0, 100]$ and a VGT position $u_{vgt} \in [0, 100]$.

3. PLANT MODELLING

In this section, we establish a plant model to be utilized in the RG as a prediction model.

3.1 Partition of Operating Condition

The behavior of a diesel engine air path system depends on operating conditions determined by the engine speed $N_e \in \mathbb{R}$ [rpm] and the load indicated by fuelling command $W_f \in \mathbb{R}$ [mm^3/stroke]. We define an exogenous input $d = [N_e \; W_f]^T \in \mathbb{R}^2$ to express the operating condition. As shown in Fig. 2, a set of exogenous inputs $\mathcal{D} \subseteq \mathbb{R}^2$ is divided into exclusive subsets $\mathcal{D}_l, l \in \mathcal{I}$, where $\mathcal{I}$ is the index set. We estabilish a prediction model at a representative operating condition in each subset $\mathcal{D}_l$ through system identification. Then, all the models are merged in one piecewise linear system switched by the exogenous input d.

3.2 Constraints

As for constraints in each subset, references in each region are assumed to be constrained. Namely, the EGR rate in the intake manifold, F_{im}, has lower and upper bounds to ensure emission performance such as NO_x reduction. The boost pressure p_{im} is expected not to exceed its maximal limit $p_{im,max}$. Moreover, maximal limits for the exhaust manifold pressure $p_{em} \in \mathbb{R}$ and the turbine speed $N_{tb} \in \mathbb{R}$ are imposed. Here, $F_{im,min}, F_{im,max}, p_{im,max}, p_{em,max}, N_{tb,max} \in \mathbb{R}$ are prescribed constants.