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Gain-scheduling control of port-fuel-injection processes

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ABSTRACT

An event-based sampled discrete-time linear system representing a port-fuel-injection process based on wall-wetting dynamics is obtained and formulated as a linear parameter varying (LPV) system. The system parameters used in the engine fuel system model are engine speed, temperature, and load. These system parameters can be measured in real-time through physical or virtual sensors. A gain-scheduling controller for the obtained LPV system is then designed based on the numerically efficient convex optimization or linear matrix inequality (LMI) technique. Simulation results show the effectiveness of the proposed scheme.

1. Introduction

Increasing concerns about global climate change and ever-increasing demands on fossil fuel capacity call for reduced emissions and improved fuel economy. Port-fuel-injection (PFI) fuel systems are widely used in vehicles today; however, direct-injection (DI) fuel systems have also been introduced to markets globally. To improve the full load performance of DI engines at high speed, Toyota introduced an engine with a stoichiometric DI system with a DI injector and an intake port injector for each cylinder (see Ikoma et al., 2006). The use of gasoline PFI and ethanol DI dual-fuel system to substantially increase gasoline engine efficiency is described by Heywood, Cohn, and Bromberg (2007). This shows that with the introduction of DI fuel systems for the internal combustion engine, PFI fuel systems will remain part of the engine fuel system for improved engine performance, which is the main motivation for revisiting the air-to-fuel ratio control problem for a PFI fuel system.

There have been several fuel control strategies developed for internal combustion engines to improve the efficiency and exhaust emissions. A key development in the evolution was the introduction of a closed-loop fuel injection control algorithm (Rivard, 1973), followed by the linear quadratic control method (Cassidy & Athans, 1980), and an optimal control and Kalman filtering design (Powers, Powell, & Lawson, 1983). Specific applications of A/F ratio control based on observer measurements in the intake manifold were developed by Benninger and Plapp (1991). Another approach was based on measurements of exhaust gas A/F ratio measured by the oxygen sensor and on the throttle position (Onder, 1993). Choi, Hedrick, Kelsey-Hayes, and Livonia (1998) also developed a nonlinear sliding mode control of A/F ratio based upon the oxygen sensor feedback. Continuing research efforts of A/F ratio control include Wang, Yu, Gomm, Page, and Douglas (2006), Alfieri, Amstutz, and Guzzella (2009), and Yildiz, Annaswamy, Yanakiev, and Kolmanovsky (2010). The conventional A/F ratio control for automobiles uses both closed-loop feedback and feed-forward control to have good steady state and transient responses.

For a spark-ignited engine equipped with a port-fuel-injection system, the wall-wetting dynamics are commonly used to model the fuel injection process; and the wall-wetting effects are compensated on the basis of simple linear models that are tuned and calibrated through engine tests. These models are quite effective for an engine operated at steady state or slow transition conditions but they are difficult for fast transient and other special operational conditions, for instance, during engine cold start. One of the approaches to model the wall-wetting dynamics during engine cold start is to describe it using a family of linear models to approximate the system dynamics at different engine cylinder head temperature, speed and load conditions, that is, to translate the fuel system model into a linear parameter varying (LPV) system.

The use of LPV modeling to control the A/F ratio of a port-fuel-injection system has been reported by Genç (2002). An LPV model is developed with manifold absolute pressure, exhaust value closing, and inlet value opening as the time-varying parameters. However, Genç (2002) does not address the issue of engine cold start. Furthermore, all LPV control synthesis methods used by Genç (2002) are based in continuous time, relying on Tustin's (bilinear)

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Nomenclature

English

c	stoichiometric air-to-fuel ratio
e	measurement for control
e_P	measurement for proportional control
e_I	measurement for integral control
$\mathcal{F}_\ell$	lower linear fractional transformation
$\mathcal{F}_u$	upper linear fractional transformation
$G(q)$	transfer function from m_i to m_c
$H(\Theta)$	feed-forward control compensated generalized plant
$\hat{H}(\Theta)$	Taylor series expansion of feed-forward control compensated generalized plant
$I(q)$	integrator
$K(\Theta)$	gain-scheduling feedback controller
$K_f(\Theta)$	feed-forward controller
$L(q)$	low-pass filter
l	pseudo-output
$M_{A_{O_2}d}$	interconnection matrix for the LFT representing A_{O_2d}
$M_{A_{O_2}^{-1}}$	interconnection matrix for the LFT representing $A_{O_2}^{-1}$
$M_{\alpha/\beta}$	interconnection matrix for the LFT for α/β
$M_{1/\beta}$	interconnection matrix for the LFT for $1/\beta$
M_γ	interconnection matrix for the LFT for γ
m_A	mass of the air trapped in the cylinder
m_c	the mass of fuel trapped in the cylinder
m_i	the mass of fuel injected
m_w	the mass of fuel residual on the wall
$P(\Theta)$	generalized plant without feed-forward control
p	pseudo-input
q	forward shift operator
T_D	transport delay
T_{O_2}	time constant of the oxygen sensor
t_s	sample period
u	control input
$\mathcal{V}_i$	the ith vertex of the parameter variation polytope
v	engine speed (rpm)
$W_1(q)$	weighting function for w_1
$W_2(q)$	weighting function for w_2
w	exogenous input
w_1	represents the deviation $(m_c/m_A - m_c/m_A^0)$
w_2	desired equivalence ratio
w_3	input to the feed-forward controller
$\tilde{w}_1$	unweighted exogenous input for w_1
$\tilde{w}_2$	unweighted exogenous input for w_2
$\tilde{w}_3$	unweighted exogenous input for w_3
x	states of the feed-forward compensated generalized plant
x_{AUG}	states of augmented plant
x_I	integrator state
x_L	low-pass filter state
x_{ww}	wall-wetting state
x_{comb}	combustion state
x_{O_2}	states of the oxygen sensor
y	equivalence ratio
y_s	measured equivalence ratio
z	error output

Greek

α	ratio of fuel delivered from the wall to the cylinder
α_0	nominal value of α
α_δ	time-varying fluctuation of α
β	ratio of the fuel entering the cylinder from injection
β_0	nominal value of β
β_δ	time-varying fluctuation of β
γ	normalized inverse engine speed
η	$\mathcal{H}_\infty$ performance bound
Θ	time-varying parameter structure
λ	barycentric coordinates

State-space realizations (Each state-space realization used in this paper are listed below in order of appearance.)

$\{A_{O_2}, B_{O_2}, C_{O_2}\}$	continuous-time state-space matrices of the oxygen sensor
$\{A_{O_2d}, B_{O_2d}, C_{O_2d}\}$	discrete-time state-space matrices of the oxygen sensor
$\{\hat{A}_{O_2d}, \hat{B}_{O_2d}, \hat{C}_{O_2d}\}$	discrete-time state-space matrices of the oxygen sensor after performing the fourth-order Taylor series approximation
$\{A, B_0, B_1, B_2, C_0, D_{00}, D_{01}, D_{02}, C_1, D_{10}, D_{11}, D_{12}\}$	discrete-time LPV system state-space matrices
$\{\hat{A}, \hat{B}_1, \hat{B}_2, \hat{C}_1, \hat{D}_{11}, \hat{D}_{12}\}$	discrete-time state-space realization after performing first-order Taylor series expansion
$\{A_L, B_L, C_L\}$	low-pass filter state-space realization
$\{\tilde{A}, \tilde{B}_1, \tilde{B}_2, \tilde{C}_1, \tilde{D}_{11}, \tilde{D}_{12}, \tilde{C}_2\}$	augmented discrete-time state-space realization
$\{\overline{A}, \overline{B}_1, \overline{B}_2, \overline{C}_1, \overline{D}_{11}, \overline{D}_{12}, \overline{C}_2\}$	discrete-time polytopic state-space realization

transformation to convert the discrete-time system to a continuous-time system, thus fixing the engine speed and sampling rate of the discrete-time system.

The contribution of this paper is as follows. First, an event-based, discrete-time LPV model for the wall-wetting and oxygen sensor dynamics with wall-wetting parameters and engine speed as scheduling variables is developed. Then an event-based, gain-scheduling controller for the derived LPV model is designed. To cope with practical situations, the discrete-time LPV control synthesis method given by Caigny, Camino, Oliveira, Peres, and Swevers (2008) is used to develop the event-based, gain-scheduling controller.

The control structure used in this study is a proportional-integral (PI) controller. PI controllers are widely used in industry since they are well understood by control engineers. The PI gains are often calibrated in a field test for the best performance as functions of system operational conditions. However, the system stability and performance are not guaranteed for all time-varying parameters. Therefore, LPV techniques are applied to design gain-scheduling PI controllers for guaranteed stability and performance for all time-varying parameters, which is expected to be well received by industrial control engineers.

The paper is organized as follows. The models and the modeling techniques used in this paper are given in Section 2. The design of the gain-scheduling controller in Section 3 is covered by first introducing the control strategy in Section 3.1. Then the feed-forward compensated generalized plant is developed in Section 3.2 and its first-order Taylor series expansion is computed in Section 3.3. Next the measurement for control is elaborated in Section 3.4. The gain-scheduling synthesis problem is stated in Section 3.5. In Section 3.6, the augmented LPV plant obtained in Section 3.4 is converted into a polytopic time-varying system, which is an LPV system with a polytopic dependency on a scheduling parameter that takes values in the unit-simplex, so that the gain-scheduling controller synthesis technique given by Caigny et al. (2008) can be performed. For comparison, a linear time-invariant feedback $\mathcal{H}_\infty$