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Supervisory control of air–fuel ratio in spark ignition engines ☆

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ABSTRACT

The problem of air–fuel ratio stabilization in spark ignition engines is addressed in this paper. The proposed strategy consists of proper switching among two control laws to improve quality of the closed-loop system. The first control law is based on an *a priori* off-line identified engine model and ensures robust and reliable stabilization of the system at large, while the second control law is adaptive, it provides on-line adaptive adjustment to the current fluctuations and improves accuracy of the closed-loop system. The supervisor realizes a switching rule between these control laws providing better performance of regulation. Results of implementation on two vehicles are reported and discussed.

1. Introduction

The requirement on vehicle tailpipe emissions is one of the main restrictions for engine development and certification. Three-way catalytic converters (TWC) installation in exhaust manifold aims at oxidizing HC and CO and reducing NOx concentration. Usually TWC peak efficiency is guaranteed if fuel–air ratio (FAR) is close to the stoichiometric value and the conversion efficiency of TWC is significantly reduced away from the stoichiometric value. Therefore, the primary objective of the FAR control system is to maintain the fuel injection in stoichiometric proportion to the ingested air flow (exception to this occurs in heavy load situations where a rich mixture is required to avoid premature detonation or for more power). Variations in the air flow affected by the driver serve as an exogenous disturbance to the system.

Due to its importance, the problem of FAR regulation has attracted significant attention during the last few decades (Cook, Kolmanovsky, McNamara, Nelson, & Prasad, 2007). Adaptive control theory (Ault, Jones, Powell, & Franklinand, 1993; Franceschi, Muske, Peyton-Jones, & Makki, 2007; Powell, Fekete, & Chang, 1998; Turin & Geering, 1995), robust control approaches (Brandstetter, 1996), fuzzy control systems theory (Ghaffari, Shamekhi, Saki, & Kamrani, 2008), neural network techniques (Huang, Liu, Javaherian, & Sin, 2008; Zhai & Yu, 2007) and learning approach (Andrianov, Manzie, & Brear, 2013; Liu, Javaherian, Kovalenko, & Huang, 2008) are successfully tested in this particular application. However, the complexity of the problem and growing demands on FAR regulation quality require new solutions. These solutions have to combine reliability and performance of robust control approaches and the accuracy and insensitivity to changes of dynamics of adaptation methods. In addition, for implementation purposes, they should have a small number of tuning parameters and clear design guidelines. Switching control theory gives a solution to this problem.

There exist many good reasons and practical motivations to use a set of controllers to regulate a single plant as opposed to one controller (Hespanha & Morse, 1999; Huang et al., 2008; Morse, 1995). In such a case the problem of trade off the advantages and disadvantages of each subsystem for modeling and control is appearing. The theory of switched systems addresses this issue proposing the proper switching laws between controllers. Application of a supervisory (switched) control algorithm may seriously improve performance of the system regulation (Efimov, Panteley, & Loria, 2008). In addition, in order to solve a complex control problem, it can be decomposed on several simpler ones with design of control laws for each of subproblems, then proper supervisor ensures switching among the controls and solution of the initial problem.

In this work, the problem of FAR regulation problem is solved considering switching between two control laws. The first one is based on robust model-based control algorithm, which ensures stability for all ranges of the system parameters and inputs, but may have accuracy shortcomings. The second control law is adaptive, it is directed at improving the quality of transient response on a dynamic fluctuation around the reference model (used in the first control). Supervisor performs activation of the adaptive control when unsatisfactory quality of the reference model is detected and, hence,

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improvement of the robust control is needed. Theoretical stability conditions of the developed supervisory control are established, and the results of implementation are reported confirming efficiency of the proposed solution.

The outline of this work is as follows. In Section 2 the detailed problem statement and some preliminaries are presented. Section 3 contains descriptions of the control algorithms. Supervisor equations are introduced in Section 4. Results of implementation are reported in Section 5. Concluding remarks are given in Section 6.

2. Problem statement

It is a well-known fact that an automotive engine is a highly nonlinear multi-variable system and derivation of its precise model is a complex process. This is a reason why the simplified models of engines are very popular in practice. These models can take into account the main features of engine processes, like the presence of time delays and nonlinearities, which are important for controller design or fault detection applications. In this work nonlinear autoregressive (NARX) model is chosen for FAR dynamics description (in this context FAR refers to the non-dimensional engine-out fuel–air ratio sometimes known as λ):

$$y(m)=\sum_{i=1}^{k}\bar{a}_i y(m-i)+\sum_{j=0}^{p}\left[\bar{\mathbf{b}}_j^T\mathbf{f}(m-j)\right]u(m-j)+\sum_{j=0}^{p}\bar{\mathbf{r}}_j^T\mathbf{d}(m-j)+v(m), \tag{1}$$

where $y\in R$ is FAR (the regulated output), $u\in[u_{min},\ u_{max}]$ is the control input (fuel pulsewidth in this work, $0<u_{min}<u_{max}<+\infty$ are actuator constraints), $\mathbf{d}\in R^n$ and $\mathbf{f}\in R^q$ are the vectors of nonlinear input terms (may contain products of the physical engine variables, which are available for measurement like engine velocity, cam phaser positions, exhaust manifold pressure, temperatures in exhaust and intake manifolds, *etc.*), $k\geq 1$ and $p\geq k-1$ are the model polynomials degrees, m is the number of current event (discrete time); $v\in R$ is a disturbance acting on the system; $\bar{\mathbf{a}}=[\bar{a}_1...\bar{a}_k]^T\in R^k$, $\bar{\mathbf{B}}=[\bar{\mathbf{b}}_0...\bar{\mathbf{b}}_p]\in R^{q\times(p+1)}$ and $\bar{\mathbf{R}}=[\bar{\mathbf{r}}_0...\bar{\mathbf{r}}_p]\in R^{n\times(p+1)}$ are the model (1) constant parameters. The advantage of NARX model consists in availability of various methods for its approximation and simplicity of control design. It is assumed that the variables $\mathbf{d}$ and $\mathbf{f}$ are independent in the control variable u and available for design, therefore, the model (1) is affine in control.

It is assumed that a dataset is given, that *a priori* has collected measured information on y, u (and other variables involved in the vectors $\mathbf{d}$, $\mathbf{f}$) for various regimes of engine operation obtained for a preliminary control. Based on the given dataset, the compact sets $\boldsymbol{D}\subset R^n$ and $\boldsymbol{F}\subset R^q$ can be computed which define admissible values for the vectors $\mathbf{d}$ and $\mathbf{f}$ respectively. Then, applying standard approaches (Ljung, 1999) the vectors of coefficients $\mathbf{a}$, $\mathbf{B}$ and $\mathbf{R}$ can be obtained as off-line approximations of $\bar{\mathbf{a}}$, $\bar{\mathbf{B}}$ and $\bar{\mathbf{R}}$. Substituting $\mathbf{a}$, $\mathbf{B}$ and $\mathbf{R}$ in (1) we represent the dynamics of FAR loop (1) with a sufficient accuracy. The residual error can be assumed bounded and modeled as a part of the exogenous disturbance v. The coefficients $\mathbf{a}$, $\mathbf{B}$ can be derived ensuring stability of the model (1) as well as stability of its inverse with respect to the control input (that corresponds to the physical nature of the engine).

Assumption 1. Polynomials defined by the vectors of coefficients $\mathbf{a}$ and $\mathbf{c}$, where $c_j=\sum_{k=1}^{q}\mathbf{b}_{j,k}$ for $0\leq j\leq p$, have all zeros with norms smaller than one.

Requirement on stability of the polynomial $\mathbf{a}$ corresponds to a physical restriction that an engine has a stable dynamics. Under this assumption and with substitution $\mathbf{f}(m-j)=1$, stabilizing controls for the system (1) can be designed applying simple inversion of its equation (inverse system is stable and, thus, the control algorithm will be realizable). The choice $\mathbf{f}(m-j)=1$ is the basic one, but some other normalized inputs may also be included in $\mathbf{f}$.

The problem is to design control $u(i)\in[u_{min},\ u_{max}]$, $i\geq 0$ ensuring practical output regulation to a given reference $y_d(i)$, $i\geq 0$, *i.e.*, the property $|y(i)-y_d(i)|\leq\Delta$ should be satisfied for all $i\geq 0$ and $\mathbf{d}\in\boldsymbol{D}$, $\mathbf{f}\in\boldsymbol{F}$ for some prescribed $\Delta>0$ providing that $|y(0)-y_d(0)|\leq\Delta$.

To this end, recall that a continuous function $\sigma: R_+\to R_+$ belongs to class K if it is strictly increasing and $\sigma(0)=0$; additionally it belongs to class K_∞ if it is also radially unbounded; and continuous function $\beta: R_+\times R_+\to R_+$ is from class KL, if it is from class K for the first argument for any fixed second one, and it is strictly decreasing to zero by the second argument for any fixed first one.

3. Control algorithms

In this section description of robust model-based and adaptive controls are presented.

3.1. Model-based control algorithm

The following is the condition of the control applicability.

Assumption 2. For all $\mathbf{f}\in\boldsymbol{F}$ it holds $\mathbf{b}_0^T\mathbf{f}\neq 0$.

Since the vector $\mathbf{f}$ is composed by measured engine variables or their nonlinear functions and products, which all have some sets of admissible values, then Assumption 2 can be easily checked for $\mathbf{f}\in\boldsymbol{F}$ and the vector of coefficients $\mathbf{b}_0$. For instance, $\mathbf{f}(i)$, $i\geq 0$ and elements of $\mathbf{b}_0$ can be all positive (that may be guaranteed by proper approximation of (1)).

Under Assumptions 1 and 2, the control law is calculated as a simple inversion of the model (1) with respect to u:

$$U(m)=\frac{1}{\mathbf{b}_0^T\mathbf{f}(m)}\Big[y_d(m)-U_{PID}(m-1)-\textstyle\sum_{i=1}^{k}a_i y(m-i) -\sum_{j=0}^{p}\mathbf{r}_j^T\mathbf{d}(m-j)-\sum_{j=1}^{p}[\mathbf{b}_j^T\mathbf{f}(m-j)]u(m-j)\Big], \tag{2}$$

where due to the presence of the disturbance v (which reflects possible unmodeled dynamics, measurement noise and approximated model errors) it is required to use an internal feedback in the form of a nonlinear PID:

$$U(m)=\frac{1}{\mathbf{b}_0^T\mathbf{f}(m)}\Big[y_d(m)-U_{PID}(m-1)-\textstyle\sum_{i=1}^{k}a_i y(m-i) -\sum_{j=0}^{p}\mathbf{r}_j^T\mathbf{d}(m-j)-\sum_{j=1}^{p}[\mathbf{b}_j^T\mathbf{f}(m-j)]u(m-j)\Big], \tag{3}$$

where $e=y_d-y$ is the regulation error, k_j, $j=\overline{1,5}$ are control parameters, which have to be determined based on real or computer experiments. The terms proportional to k_1 and k_5 are responsible for proportional feedback (k_1 for local regulation, and k_5 for big deviations of $e(m)$, appearance of two gains helps to improve quality of feedback). The terms proportional to k_2 and k_3 correspond to integral and differential actions respectively. The term with k_4 allows small matched disturbances to be compensated. The control (2) under substitution $u(m)=U(m)$ ensures the model inversion and the following closed loop dynamics:

$$y(m)=y_d(m)-U_{PID}(m-1)+v(m).$$

Without U_{PID} the control (2) forms the so-called feedforward part of the regulator, that does not contain any feedback errors (it depends on the current and past values of the inputs and outputs of the engine dynamics and the approximated coefficients of the model).

The control (2) cannot be realized in practice since there exist constraints on admissible control amplitudes, *i.e.* it should be within the following bounds: $u_{min}\leq u\leq u_{max}$. The implementation of a