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# Advanced model based air path management using a discrete-angular controller in idle-speed context

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**Abstract:** This paper aims to present an original methodology to design a controller for the air path management considered as a nonlinear system that is presented as a periodic discrete Takagi-Sugeno (TS) model. A transformation is realized to translate the periodic behavior into a classic discrete model using the different sample times. The controller gains are obtained solving LMI problems with uncertainties. The presented results are illustrated through the control of an Internal Combustion (IC) engine during the idle speed phase. Simulation results are provided to emphasize the utility of the methodology.



*Keywords*: ***Gasoline engine, idle speed control, throttle controller, Takagi-Sugeno discrete controller, LMI-based methodology***

## 1. INTRODUCTION

This paper presents a methodology based on nonlinear stabilization techniques applied to an Internal Combustion (IC) engine. It is well known that a gasoline engine is working through several phases, for example a 4-strokes engine. Including that, the system can be described as a periodic system. Such systems have been studied in the past by the work of (Bittanti and Colaneri, 2009).

Concerning the methodology, some nonlinearities appear among the modelling process. Instead of the classical linearization often used in industry, the authors offer to use the Takagi-Sugeno (TS) representation (Takagi and Sugeno, 1985). This methodology ensures to get an exact representation of the system, and an important work has already been realized in designing efficient tools for stability and stabilization of these TS models (Tanaka and Wang, 2001; Guerra and Vermeiren, 2004; Lendek *et al.*, 2015). Moreover, some methodologies have been developed to construct special Lyapunov functions and to deal with periodic TS models such as (Kerkeni *et al.*, 2009; Lendek, Lauber and Guerra, 2013).

Concerning the application, plenty of works have been done on IC engine model and control. For example, it appears that using the discrete-time domain may be more representative than the continuous-time domain according to (Yurkovich and Simpson, 1997). Additionally, using LMI-based design for automotive application has been proved to be efficient and accurate, such as presented in (Dussy *et al.*, 1998).

Engine control can be realized through several inputs, but for this paper we mainly focus on throttle control. It has been subject to many publications, among them we can quote (Eriksson and Nielsen, 2000) that controls the throttle based on a non-linear model, (Khiar *et al.*, 2007) for the manifold pressure control, (Abbas and Werner, 2008) using neural networks for the system representation, (García-Nieto *et al.*, 2009) for application to a diesel engine or (Thomasson and Eriksson, 2011).

The context of this study is the idle speed control, a famous automatic control problem whose goal is to stabilize the engine speed around a reference value, as low as possible to reduce consumption but not too low to avoid stalling. In idle speed control, two inputs can be used: The throttle angle and the spark advance angle, which corresponds to the degrees before Top-Dead Center (TDC) when the air-fuel mixture is ignited.

In order to control spark advance angle, moreover if the control aims to be tuned for each cylinder, there is a need for two elements: cylinder-to-cylinder observers such as developed in (Kerkeni, Lauber, *et al.*, 2010; Laurain, Lauber and Reinaldo Martinez Palhares, 2015) and efficient throttle control on which the spark advance controller can rely on. This is the main purpose of this paper.

The originality of this paper is to propose applying LMI-based techniques on a particular model (hybrid model) transformed into, first, a periodic discrete-time nonlinear state-space representation, and then, non-periodic one. These techniques lead to a controller design that includes the singularities of the studied system. Thanks to such a controller, we can pilot the throttle position during idle speed phase.


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The paper is organized as follows: In Section 2, the used engine model is described. Section 3 details the controller design. Finally, in section 4, some simulation results highlight the proposed methodology.

## 2. ENGINE MODEL

### 2.1 Continuous-time domain model

Several models are presented in the literature for IC engines like (Eriksson *et al.*, 2002; Guzzella and Onder, 2010), but only a few of them use the throttle angle and the individual spark advance angle (for each cylinder) as inputs. Because the main goal is to control cylinder-per-cylinder spark advance, there is a need for a model that uses explicitly this variable, even if such a model is too complex for the throttle control.

Among these models, (Balluchi *et al.*, 2010) proposes a hybrid model (i.e., a continuous-time model triggered by discrete-time events) where both throttle and individual spark advance angle appear as inputs and can be controlled. Consequently, this model is chosen for our LMI-based design controller such as it has been used in our previous works on observers (Laurain, Lauber and Reinaldo Palhares, 2015).

Even if some equations are from physics (such as the pressure dynamics for example, which come from the perfect gases equation), most of the phenomenon are described by polynomial equations whose coefficients are given for a Magneti Marelli engine (see Table 1).

**Table 1. Engine parameters**

| | | | | |
|---|---|---|---|---|
| $RT/V$ | $c_0$ | $c_1$ | $c_2$ | $c_3$ |
| $2.152e^{5}$ | $8.279e^{-4}$ | $3.041e^{-6}$ | $8.5e^{-8}$ | $2.245e^{-9}$ |
| $\tau_{thr}$ | $s_0$ | $s_1$ | $s_2$ | $a_0$ |
| $8.35e^{-2}$ | $7e^{-4}$ | $3.9e^{-4}$ | $5.78e^{-5}$ | $-0.625$ |
| $b_0$ | $e_0$ | $h_0$ | $h_1$ | $h_2$ |
| 59.68 | $-1074$ | 0 | $1.265e^{5}$ | $2.145e^{9}$ |

As described before, this model is a hybrid model. Some methodologies have already been published concerning the control of hybrid models (Balluchi *et al.*, 2013; Di Cairano *et al.*, 2014). However, this paper proposes to apply LMI-based techniques for the controller design, that is why there is a need for this model to be transformed from a hybrid model to a periodic non-linear model.

In fact, the discrete-events that are triggering the continuous-time part of the hybrid model mainly depend on the engine phase. Using the periodic representation that has been developed in (Bittanti and Colaneri, 2009), we can build a periodic state-space representation that is equivalent to the previous hybrid model from (Balluchi *et al.*, 2010) :

$$\dot{x}(t) = f^{p}\left(x(t), u(t), T_{load}(t)\right) \tag{1}$$

The state vector is chosen with 10 variables, including measured and non-measured ones. It is composed as follows: $x_1 = n$ (crankshaft speed, in rpm), $x_2 = T_{air}$ (torque produced by the air path in Nm), $x_3 = p$ (pressure in the intake manifold in mbar), $x_4 = \alpha$ (throttle angle in degrees), $x_5 = \eta$ (contribution of the spark advance), $x_6 = \varphi$ (spark advance angle before top-dead center, in degrees), $x_7^i = \dot{m}_{air}^i$ (mass air flow in the i-th cylinder) for $i \in \{1, \ldots, 4\}$. The state-space representation has also an input vector which is composed by $u_1 = cmd_{thr}$ (command of the throttle angle in degrees) and $u_2 = cmd_{spk}$ (command of the spark advance angle, same for all the spark plugs).

$f$ is a non-linear function that depends on the state, the input vector and the load torque $T_{load}$ which is the resistant torque applied to the engine. For example, $T_{load}$ can be the torque demand from the starter to turn on an electronic device (like Air Conditioning system). $p$ denotes the periodicity of the model (i.e. the engine) through several phases depending on the crankshaft degrees and presented in Table 2.

**Table 2. Engine phases**

| Phase / Cylinders | C1 | C2 | C3 | C4 |
|---|---|---|---|---|
| P1 (0° to 180°) | I | C | H | E |
| P2 (180° to 360°) | C | E | I | H |
| P3 (360° to 540°) | E | H | C | I |
| P4 (540° to 720°) | H | I | E | C |

Where “I” stands for “Intake”, “C” is for “Compression”, “E” means “Expansion” and “H” translates the “Exhaust” phase.

### 2.2 Periodic continuous-time Takagi-Sugeno model

As presented in the introduction, this paper aims to use a different method than the classic linearization of the nonlinearities. Since several years ago, the representation of (Takagi and Sugeno, 1985) has been developed, used and provided with plenty of tools and techniques for designing observers and controllers.

A Takagi-Sugeno model (TS) is a convex combination of several local models. The huge interest of such a method is that it can provide an exact representation of an important class of non-linear systems. These local models are weighted by non-linear coefficients, the membership functions, which have to verify the property of convex sum:

$$\sum_{i=1}^{r} h_i(z) = 1 \tag{2}$$