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Implementing advanced Takagi-Sugeno controllers: application to throttle control of a gasoline engine

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Abstract: This paper is dedicated to the implementation process of advanced Takagi-Sugeno controllers. The considered application is the control of the throttle of a gasoline engine running at idle speed. In order to design a model-based control, a model is first obtained and identified with an engine test bench. Since it involves nonlinearities, a Takagi-Sugeno representation is expressed. Due to the complexity of the model, a simple TS controller cannot be obtained after applying the Lyapunov methodology. Then, an advanced non-PDC controller has to be considered. LMI conditions are obtained through the direct Lyapunov direct method. However, the real-time matrix inversion involved in the non-PDC structure makes the implementation difficult or impossible. An alternative controller is then designed to have similar performances without any matrix inversion. Then, the controller is implemented in the industrial-like Electronic Control Unit of the engine test bench. Experimental results are provided to illustrate the efficiency of the proposed advanced Takagi-Sugeno controller.

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Keywords: Takagi-Sugeno modelling and control ; non-PDC controller ; alternative controller ; real implementation ; gasoline engine control ; idle speed conditions; throttle control

1. INTRODUCTION

Implementing advanced control laws remains the heart of the problem when application to an industrial system is considered. Indeed, the electronic control units (ECU) where the controller is developed, has usually low power and low memory. It means that the complex control structure designed in theory can be costly or impossible to compute.

Since most of the applications deal with nonlinear systems, the Takagi-Sugeno (TS) representation is considered. Instead of linearizing or approximating, an exact representation is obtained and what is proved on the Takagi-Sugeno model is also valid on the nonlinear system. Moreover, TS models come with various model-based controllers (Tanaka and Wang, 2001). The most simple is the Parallel Distributed Compensation (PDC) developed in (Wang et al., 1996). Better performance and less conservative results can be obtained by the use of a more complex and advanced controller, called non-PDC (Guerra and Vermeiren, 2004).

The considered application is a gasoline engine running at idle speed, i.e. the driver does not apply any command on the pedal and the throttle valve is controlled to maintain the speed at a reference, not too high to avoid useless fuel consumption, but not too low to avoid stalling. Indeed, when an electronic device is turned on, such as the air conditioning, a load torque is applied on the gasoline engine and may stall if the speed is too low. This is a classical control problem of reference tracking and external disturbance rejection.

Idle speed control has been hugely investigated in the literature (Ye, 2007; Ashok et al., 2016). Adaptive controller has been developed in (Yildiz et al., 2011) to avoid dealing with nonlinear model. Model-based methods include the model-predictive control which has received a growing interest since it can include industrial constraints (Di Cairano et al., 2012; Hrovat et al., 2012). However, these techniques do not deal directly with nonlinearities. In addition, the implementation of such control laws has a computational constraint since it involves evolutive algorithms that are costly for an industrial ECU.

This paper focuses on Takagi-Sugeno models and controllers for their ability to manage nonlinear systems. While advanced TS controllers have been developed in theory (Lendek et al., 2015) and applied to the idle speed problem in simulation (Laurain et al., 2016a), the implementation of such an advanced controller has not been considered yet in the automotive industry. Indeed, the use of real-time matrix inversion involved in the advanced controller structure can be difficult to compute for an industrial ECU. That is why an alternative controller, with similar performance but no matrix inversion, is designed before implantation on an engine test bench.

This paper is divided into several sections: Section 2 details the notation of the theoretical parts as well as the experimental setup used. Section 3 presents the engine as a nonlinear system represented under the Takagi-Sugeno representation. Section 4 details the design of an advanced TS controller. Section 5 presents simulation results of the

advanced TS controller. Section 6 details the design of the alternative controller. Section 7 is dedicated to real implementation of the alternative controller in an ECU and experimental results. Finally, Section 8 offers some conclusions and perspectives.

2. PRELIMINARIES

2.1 Notations

For the rest of the paper, a discrete nonlinear state space representation affine in control is written:

$$x(k+1) = A(x) \cdot x(k) + B(x) \cdot u(k) \quad (1)$$

and the associate Takagi-Sugeno representation:

$$x(k+1) = \sum_{i=1}^r h_i(k) (A_i \cdot x(k) + B_i \cdot u(k)) \quad (2)$$

where r is the number of rules and A_i and B_i are the local linear models. For short notation, $\sum_{i=1}^r h_i(k) \cdot A_i = A_z$ and:

$$x(k+1) = A_z \cdot x(k) + B_z \cdot u(k) \quad (3)$$

Similarly, it is possible to define $\sum_{i=1}^r h_i(k-1) \cdot A_i = A_{z-}$ and

$$\sum_{i=1}^r h_i(k+1) \cdot A_i = A_{z+}$$

2.2 Experimental setup

For the identification, validation and experimental phases, the engine test bench located at LAMIH, Valenciennes is used. It is composed of a Renault engine D4FT 1.2L with turbocharger. It is equipped with commercial sensors and actuators. The Electronic Control Unit (ECU) is programmable but commercial-like, e.g. it has low power and low memory. Getting control laws that are suitable for these industrial computers is the heart of the problem when considering application of advanced Takagi-Sugeno controllers.

3. TAKAGI-SUGENO ENGINE MODEL

3.1 Engine model

As for the application, the considered gasoline engine is adapted from (Laurain et al., 2016a). It is based on an hybrid model coming from (Balluchi et al., 2010) and converted as a periodic state-space representation (SSR):

$$\dot{x}_\alpha(t) = A_\alpha^p \cdot x_\alpha(t) + B_\alpha^p \cdot u_\alpha(t) \quad (4)$$

Since an engine is equipped with sensors and actuators that are depending on the crankshaft angle $\theta(t)$, it is valuable to

convert the model in a particular discrete domain: the crank-angle domain developed by (Yurkovich and Simpson, 1997). Thanks to such a transformation, with a suitable sampling value, i.e. $T_s^\theta = 180$ crankshaft degrees or triggering every engine cycle, it is possible to express unmeasured values such as the produced torque in function of measured values, as presented in (Laurain et al., 2016a). It stands that the periodic state-space representation can be converted in the crank-angle domain and it becomes a non-periodic discrete SSR:

$$x_\alpha^\theta(k+1) = A_\alpha^\theta \cdot x_\alpha^\theta(k) + B_\alpha^\theta \cdot u_\alpha^\theta(k) \quad (5)$$

where the state vector is depending on engine values, i.e. $x_\alpha^\theta(k) = [n(k) \ n(k-1) \ n(k-2) \ \alpha(k-2)]^T$ with $n(k)$ the engine rotational speed (in rpm) and $\alpha(k)$ the angular position of the throttle (in degrees). The input $u_\alpha^\theta(k)$ is the throttle reference position (in degrees) and the state and input matrices are given as:

$$A_\alpha^\theta = \begin{bmatrix} 1 + a_0 \cdot NL_3(k) & 0 & 0 & NL_1(k) \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 - \frac{NL_2(k)}{\tau_{thr}} \end{bmatrix} \quad B_\alpha^\theta = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{NL_2(k)}{\tau_{thr}} \end{bmatrix} \quad (6)$$

with the following nonlinearities:

$$\begin{cases} NL_1(k) = \frac{T_s^\theta \left(\frac{a_1 \cdot \phi(k-2)}{\lambda(k-2)} + \frac{a_2 \cdot \phi(k-2)^2}{\lambda(k-2)} + e_0 \right)}{6 \cdot \alpha(k-2) \cdot n(k)} \\ \phi(k) = \frac{30 \cdot \alpha(k) \cdot \varphi(k)}{n(k)} \\ NL_2(k) = \frac{T_s^\theta}{6 \cdot n(k-2)}, NL_3(k) = \frac{T_s^\theta}{6 \cdot n(k)} \end{cases} \quad (7)$$

where $\varphi(k)$ is the spark advance in degrees before Top Dead Center ($^\circ$ BTDC) and represents the moment where the air-fuel mixture is ignited.

3.2 Takagi-Sugeno model

Instead of linearizing the model or approximating the nonlinearities, the Takagi-Sugeno exact representation is considered. The collection of local linear models is obtained through the sector nonlinearity approach. The linear models are triggered with the membership functions $h_i(k)$ verifying

the property of convex sums, i.e. $\sum_{i=1}^r h_i(k) = 1$ and $h_i(k) > 0$

. The following Takagi-Sugeno model with 3 nonlinearities is obtained:

$$x_\alpha^\theta(k+1) = A_{\alpha,z}^\theta \cdot x_\alpha^\theta(k) + B_z^\theta \cdot u_\alpha^\theta(k) \quad (9)$$

While considering real-time implementation, the number of nonlinearities has to be reduced to the minimum. Indeed, the complexity of a control law can be measured by the number of basic operations (addition, multiplication...) it involves. By considering Takagi-Sugeno fuzzy controllers where the membership functions are computed every sampling value, such as a PDC in (Wang et al., 1996) or a non-PDC in (Guerra and Vermeiren, 2004), the number of operations is directly depending on the number of rules or local models.

The Takagi-Sugeno model has 3 nonlinearities. However, two of them have similar structure, i.e. depending on the engine speed at k and $k-2$ samples. Since the application case is the engine running at idle speed, the hypothesis can be taken that the engine speed between two samples is varying by 10%, i.e.

$$n(k) = \frac{1}{1+\Delta} n(k-2) \quad (10)$$

Where Δ represents the uncertainty which is bounded. As presented in (Laurain et al., 2016a), an uncertain Takagi-Sugeno model with 2 nonlinearities can be obtained:

$$x_\alpha^\theta(k+1) = (A_{\alpha,z}^\theta + \Delta A_z) x_\alpha^\theta(k) + B_{\alpha,z} \cdot u_\alpha^\theta(k) \quad (11)$$

3.3 Identification and validation

Now that the Takagi-Sugeno model has been obtained, the constant parameters have to be identified for real-time implementation in the engine test bench. Several datasets recorded from the engine are used. Figure 1 and Figure 2 present the identification result of the model (5) given by matrices (6) based on one dataset among them. They represent respectively the identification of the throttle dynamics and the idle speed model.

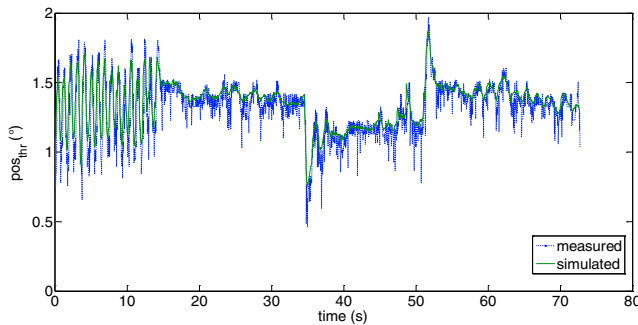


Fig. 1. Identification of the throttle model (simulated in green, measured in dotted blue)

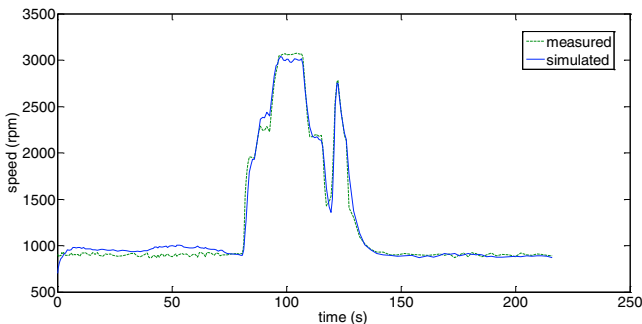


Fig. 2. Identification of the idle speed model (simulated in blue, measured in green)

As one can see, the simulated signal fits the measured one. The following parameters are given in Table 1. Validations are realised to assess the accuracy of the obtained model using several engine datasets different from the ones used in identification. Figure 3 and 4 present the validation results of respectively the throttle model and the idle speed model. If the simulated signal does not fit perfectly the measured one, at least it catches the dynamic behaviour. Since the controller structure will include an integral action, the errors are going to be compensated. The engine model is suitable for controller design.

Table 1. Engine parameters

$\tau_{thr} = 0.021815$	$a_0 = -0.3432$	$a_1 = 39.9705$
$a_2 = 340.9411$	$e_0 = 281.9019$	

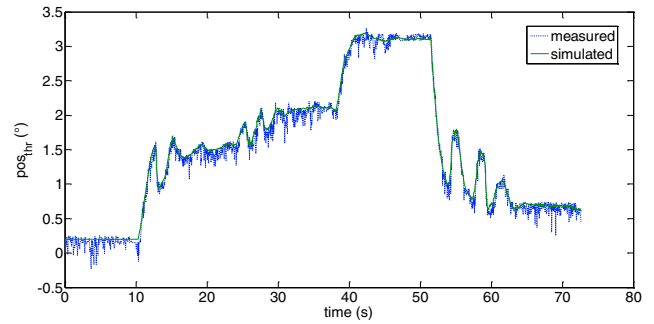


Fig. 3. Validation of the throttle model (simulated in green, measured in dotted blue)

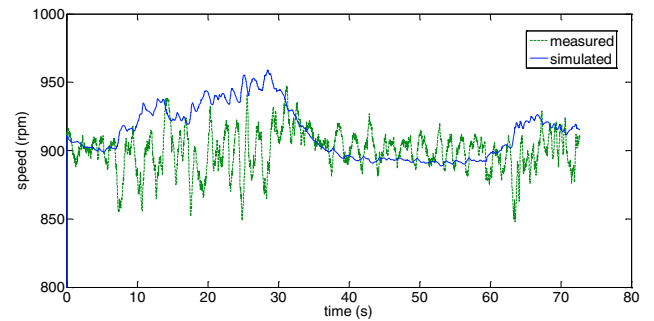


Fig. 4. Validation of the idle speed model (simulated in blue, measured in green)

4. TAKAGI-SUGENO ADVANCED THROTTLE CONTROLLER DESIGN

4.1 Integral action

Regarding the use of applicative Takagi-Sugeno controllers, the aim is not always to bring the state back to zero. Indeed, the objective in several applications is to track a reference and to reject external disturbances. Then, the controller structure has to be modified. The state is augmented in order to include the error between the reference and the current input, i.e. $e_\alpha^\theta(k) = y_{\alpha,ref} - y_\alpha^\theta(k) = y_{\alpha,ref} - C_\alpha^\theta \cdot x_\alpha^\theta(k)$ and the

new state $\bar{x}_\alpha^\theta(k) = [x_\alpha^\theta(k) \ e_\alpha^\theta(k)]^T$. The matrices are modified according to this new state.

4.2 PDC controller design

A first Takagi-Sugeno fuzzy controller is designed. In order to get information from the membership functions, they are included in the structure of the controller by using a PDC controller from (Wang et al., 1996):

$$u_\alpha^\theta(k) = -K_{\alpha,z}^\theta \cdot \bar{x}_\alpha^\theta(k) \quad (12)$$

Due to the complexity of the model, this controller is not able to stabilize the closed-loop system by the Lyapunov direct method, whatever the considered Lyapunov function according to (Laurain et al., 2016a). There is a need to investigate more complex and advanced Takagi-Sugeno controllers.

4.3 Advanced non-PDC controller design

In order to obtain more advanced Takagi-Sugeno controllers, a non-PDC structure has to be explored. Among the existing advanced non-PDC controller, the one that involves a fuzzy matrix inversion has good performance and less conservativeness (Guerra and Vermeiren, 2004):

$$u_\alpha^\theta(k) = -K_{\alpha,z}^\theta \cdot (H_{\alpha,z}^\theta)^{-1} \cdot \bar{x}_\alpha^\theta(k) \quad (13)$$

Remark 1: It is possible to replace the fuzzy matrix $H_{\alpha,z}^\theta$ by a non-quadratic Lyapunov matrix P_z but the problematic about implementing advanced controller with real-time matrix inversion still remains.

In order to assess the stability of the closed-loop system, the direct Lyapunov method is used. In discrete, the Lyapunov function should decrease between two samples, i.e. $V_\alpha(k+1) - V_\alpha(k) < 0$ with the delayed non-quadratic Lyapunov function (Lendek et al., 2015):

$$V_\alpha(k) = \bar{x}_\alpha^\theta(k)^T \cdot P_z^{-1} \cdot \bar{x}_\alpha^\theta(k) \quad (14)$$

By solving the LMI conditions presented in Theorem 1 of (Laurain et al., 2016a), the gains of the controller are obtained.

5. THROTTLE CONTROL: SIMULATION RESULTS

In order to assess the efficiency of the advanced Takagi-Sugeno controller (13) for the considered application, simulations are realized. The nonlinear engine model (4) is simulated and fed with engine datasets from the test bench, i.e. the values of air-fuel ratio, spark advance and so on are based on real measurements (and so there is no need to add artificial noise to get realistic simulations). The Takagi-Sugeno controller is implemented in Simulink and generates a command signal for the position of the throttle. A scenario is designed to evaluate both reference tracking

($y_{ref} = 900rpm$) and external disturbance rejection considering the load torque profile designed based on experimental observations displayed in Figure 5.

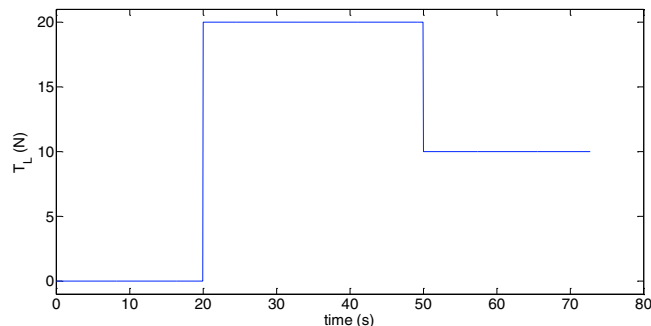


Fig. 5. Load torque profile

Figure 6 and 7 present the output (engine speed) and the command input respectively. As one can see, the advanced Takagi-Sugeno controller succeeds in tracking the reference and rejecting the disturbance, even if the controller is triggered every engine cycle.

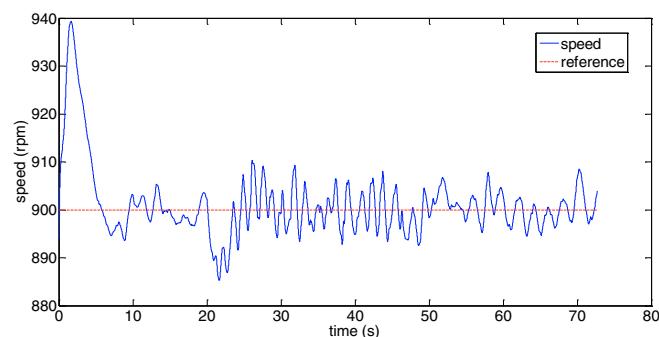


Fig. 6. Engine idle speed

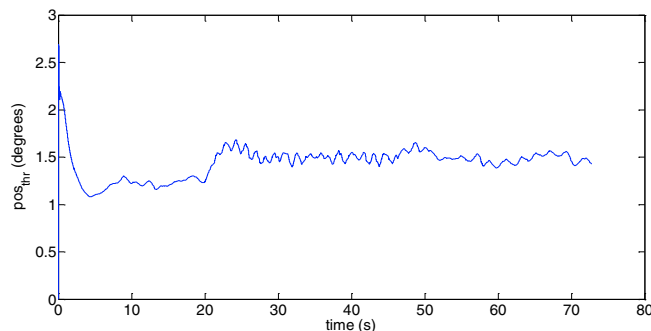


Fig. 7. Throttle command signal

However, using a advanced Takagi-Sugeno controller (13) represents a major problem while considering a real-time implementation. Indeed, the structure of the control law involves a real-time matrix inversion, which can be costly to compute for an industrial ECU. An alternative controller, with same performance but without any matrix inversion, has to be designed.

6. TAKAGI-SUGENO ALTERNATIVE THROTTLE CONTROLLER

6.1 Real-time matrix inversion problem

As already mentioned, the complexity of a control law is expressed in function of basic operations. Inverting a matrix in real-time can be done through several methods, one of the most efficient is the Strassen's algorithm whose complexity is $C(M^{-1}) = 5.64 \cdot n_M^{\log_2 7}$. This complexity is depending on the size of the inverted matrix. When one wants to implement an advanced Takagi-Sugeno in a low power ECU, these considerations have to be taken into account. Indeed, computing a matrix inversion in real-time is costly, or even impossible (case of the ECU of the engine test bench of Valenciennes). That is why finding alternative control laws, with similar performance but no matrix inversion, is crucial for one who has to implement Takagi-Sugeno controllers.

6.2 Alternative controller design

In order to implement the advanced Takagi-Sugeno controller that has been developed to control the throttle position, an equivalent controller has to be obtained first. Several methods exists to get an alternative controller to a non-PDC, as detailed in (Laurain et al., 2017a). Two different methods are presented, one involving a multi-sums matrix (CATS controller) and one involving an observer to approximate the matrix inversion (ECLATS controller). According to the size of the state matrix of the considered Takagi-Sugeno engine model, the CATS approximation is less costly for an ECU : a non-PDC controller needs 1018 operations while the alternative one needs 829 operations. The systematic methodology to design a CATS controller is detailed in (Laurain et al., 2016b). Let us first consider a two-CATS controller:

$$\tilde{u}_\alpha^\theta(k) = -F_{\alpha,z} \cdot G_{\alpha,zz}^\theta \cdot \bar{x}_\alpha^\theta(k) \quad (15)$$

The main idea behind the alternative controller design is to approximate the inverted fuzzy matrix by:

$$\left((H_{\alpha,z}^\theta)^{-1} - G_{\alpha,zz}^\theta \right)^T \left((H_{\alpha,z}^\theta)^{-1} - G_{\alpha,zz}^\theta \right) < \gamma I \quad (16)$$

where γ is the accuracy of the approximation. Matrix inequalities are then obtained. Instead of removing the membership functions with relaxations, they are triggered in a compact set $E = \{0 : 0.25 : 1\}$. LMI conditions are obtained and solved to get the gains of the alternative controller (15).

Next step of the methodology is to study the stability by obtaining the Lyapunov matrices and computing the eigenvalues.

In the study case of the idle speed, the two-sums CATS controller approximates the advanced non-PDC controller with an accuracy of $\gamma = 0.0014$. The gains are obtained, i.e. 16 matrices of size 5-by-5 that are not detailed in the paper. The new controller (15) has similar performance than the advanced TS controller (13) but without the matrix inversion. Since the controller has been tested in simulation and approximated to fit in an industrial ECU, it is now ready for real-time implementation.

7. THROTTLE CONTROL: EXPERIMENTAL RESULTS

The alternative controller (15) is implemented in the ECU of the engine test bench. The other actuators are controlled by industry-like look-up tables for the spark advance and a PDC controller for the fuel injection to control the air-fuel ratio, designed according to the methodology in (Laurain et al., 2017b).

A scenario is designed with varying speed reference including steps and ramps to assess reference tracking. Figure 8 and 9 present the measured engine speed and the associated throttle position control. As one can see, the alternative controller that approximates performance of the non-PDC one, is able to track varying reference and to maintain the engine speed in a short window near the desired value. These experimental results validate the efficiency of the proposed methodology to design advanced TS controller that can be embedded in an industrial ECU for real-time applications.

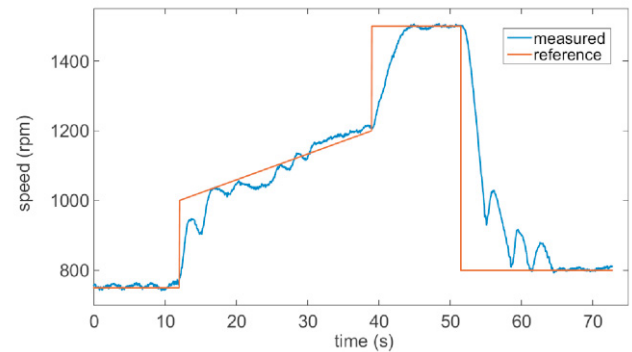


Fig. 8. Measured engine speed signal

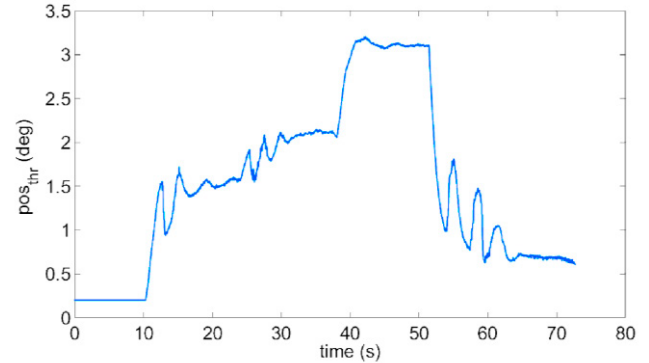


Fig. 9. Measured throttle command signal

7. CONCLUSIONS

The paper deals with implementation of advanced Takagi-Sugeno controllers and the problems that may occur due to the limited capacity of the industrial ECUs. Indeed, as illustrated through the application of the idle speed control, the complexity of the model may need an advanced controller to stabilize the closed-loop system. If this kind of controllers have demonstrated its efficiency in theory, their implementation remains difficult due to the real-time matrix inversion. An alternative controller has been designed based on multi-sums matrix, with the same performance as the complex TS controller but without matrix inversion. Experimental results have illustrated the feasibility of the

whole methodology as well as performance of the proposed controller for managing the idle speed of a gasoline engine. As a theoretical point of view, the methodology of designing an alternative controller can be extended to the case of descriptor systems where fuzzy matrix inversions are involved in both the model and the controller. As an application point of view, a second actuator can be included to control the idle speed: the spark advance.

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