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Control strategy for the air path dynamic system

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Abstract— **This paper focuses on the control of diesel HCCI engine air path. We propose a control strategy based on Recursive Model Free Controller (RMFC). This kind of controller is simple to design and it needs only the outputs of the system. On other hand, in order to estimate the state variables, an observer is used and its convergence is performed by using Lyapunov asymptotic stability and is formulated in the format of Linear Matrix Inequalities (LMI) to obtain observer gains. The proposed approach while possessing a simple structure proves a good performance in term of static state error with an accepted setting time. The proposed strategy has been successfully evaluated using a professional advanced diesel engine simulator AMEsim(LMS) platform in co-simulation with SIMULINK.**

Index Terms— **Diesel Engine, Air path, Recursive Model Free Controller, Takagi-Sugeno models.**

I. INTRODUCTION

Diesel engines are recognized as the most common and preferred solutions for distributed power generating systems in numerous applications, such as automotive vehicles, ships, cranes, and electric power generators due to their fuel efficiency and durability. Until now, these advantages were counterbalanced by the high level of oxides of nitrogen (NO_x). A very effective way to reduce the formation of NO_x during combustion is to use a cleaner combustion mode as the Homogenous Charge Compression Ignition (HCCI). This has become of major interest in recent years.

This combustion is a hybrid of spark ignition and compression ignition engine concept. As in a spark ignition engine, a homogeneous fuel-air mixture is created in the intake manifold system. During the compression stroke the temperature of the mixture increases and reaches the point of auto ignition, similar to a compression ignition engine. Small mismatches between the mixture in the cylinder (air-burned gas-fuel) and the reference mixture can have dramatic effects. It generate extra noises, pollution and possible stall. The general problem of combustion control can be decomposed into three control subproblems : the air path control, the cylinder balancing control problem and the fuel path control issues. This paper addresses only the air path control issues. The nonlinear multivariate nature of the air path system and the non-minimum phase behavior make this control design problem complicated.

The problem of the air path control has been greatly studied and still remains an active research area [1]. In the literature, most studies consider both intake : pressure and air flow using Exhaust Gas Recirculation (EGR) valve and Variable Geometry Turbocharger (VGT). As such, a multivariate linear feedback controller [7],[11] based on gain scheduling PI controllers is presented. It coordinates the EGR valve and the VGT to fully utilize their joint effect on engine emission performance. A Constructive Lyapunov Control (CLF) design for turbocharged diesel engine [3] based on nonlinear control was employed . The CLF approach is constructed using an input-output linearization. The H_∞ robust controllers [4] have been used in order to investigate the effect of the uncertainty parameterization type on their performances for the air path diesel engine. A simple motion planning strategy for controlling the air path dynamics of diesel engine is proposed [2]. An approach based on a data-based grey-box Linear Parameter Varying (LPV) model as well as on the gain scheduled technique H_∞ for the controller design is exposed in [14]. A nonlinear control [1] regulating both intake and exhaust pressure for the EGR valve and the VGT in a common-rail diesel engine has been developed. The VGT and EGR controllers are based on a nonlinear diesel engine model.

By taking into account the gear-box configuration, the position of the accelerator fixed by the driver is turned into a torque control objective under the form of Indicated Mean Effective Pressure (IMEP) set point. Then, the set points for the intake manifold pressure and the Burned Gas Ratio (BGR) are inversely given by experimentally calibrated static maps operating range. The contribution of this paper is to propose a new control strategy based on Recursive Model Free Controller (RMFC) with the EGR valve and the VGT as actuators to reach the set points given by the torque controller. The proposed approach while possessing a simple structure should prove a good performance in term of static state error with an accepted setting time.

The BGR is not measured on the considered engine. So in order to develop an air path control, it has to be

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estimated. For that purpose a mean value model of diesel engine is presented and transformed into a Takagi-Sugeno (TS) fuzzy model [8]. A TS model is a nonlinear model composed of linear models blended together with some nonlinear functions. The interest is to obtain an exact representation of a nonlinear model in a compact set of state variables. One way to derive one TS model from a nonlinear model is to use two nonlinear functions (called membership functions in the TS model) to describe each nonlinearity. This systematic method is called the sector nonlinearity approach [10]. Then, an air path observer is developed. To prove the observer convergence, stability conditions of autonomous fuzzy systems formulated in [9] have been applied.

This paper is organized as follows. After having introduced the air path control problem in section II, a mean value model of diesel engine is presented and transformed into a TS model in section III. Then, an air path observer for the BGR estimation is developed in section IV. The proposed strategy control based on RMFC is presented in the section V. This strategy is successfully evaluated using an advanced diesel engine professional simulator AMEsim(LMS) in the section VI. Conclusion and future recommendation for a future work are finally presented in the last section.

II. THE CONTROL PROBLEM

The general problem of combustion control can be decomposed into three control issues : the air path control, the cylinder balancing control and the fuel path control issues. In this work, we are interested only in the air path control issues.

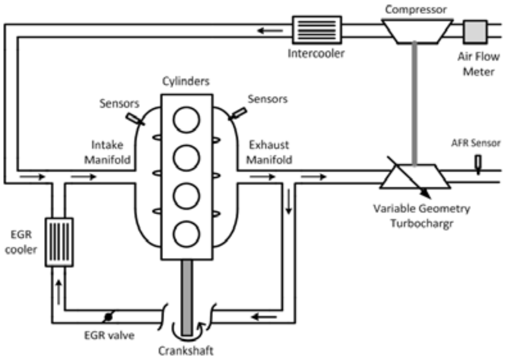

Fig. 1. A schematic picture of an air path system

The diesel engine considered in this paper is a four-cylinder engine with a high-pressure Exhaust Gas Recirculation circuit (EGR) and a Variable Geometry Turbocharger (VGT). A schematic picture of an air path system is shown in Fig.1. The air entering the engine is measured by an Air flow Meter. It then passes through the compressor, enters the intake manifold, and flows into the cylinders. The fuel is injected directly into the cylinders and burned, producing torque on the crank shaft. The hot exhaust gas is pumped out via the exhaust manifold. Part of the exhaust gas flows from the exhaust manifold through the turbine out of the engine and the other part is recirculated back into the intake manifold through the EGR valve. The turbine takes the energy from the exhaust gas to power the compressor. The scheme also shows the intercooler and the EGR-cooler that are used to reduce the intake manifold temperature.

The engine is equipped with sensors measuring : the intake manifold temperature, the intake manifold pressure, the exhaust manifold temperature and the exhaust manifold pressure. It is also equipped with the AIR/Fuel Ratio sensor located downstream the turbine. It reflects the composition in the exhaust manifold. The control inputs to the engine are the injected fuel, the EGR-valve and the VGT. The speed of engine is also considered to be an input.

In the air path control, it is desirable to control the masses aspirated by the cylinder ($M_{asp,air}$ and $M_{asp,bg}$) with two air path actuators (EGR valve and VGT). In practical situation, the considered masses can not be measured. Equivalent variables can be considered. Controlling those two masses is equivalent to controlling the intake manifold pressure P_{int} (being a reflection of $M_{asp,air} + M_{asp,bg}$) and the burned gas rate F_{int} (representing to ratio $\frac{M_{asp,bg}}{M_{asp,air}+M_{asp,bg}}$). Set points are often chosen to to reduce the NO_x emissions. In this context, the aim of this work is to design a new multivariate control strategy with the EGR valve and the VGT as actuators of these masses to reach the set points given by the torque controller. The proposed approach should have a simple structure, while ensuring good performance in terms of static state error and setting time.

The control problem that we need to address is a problem for two outputs and two inputs system. The control inputs are the VGT actuator position and the EGR valve normalized effective area. Both are bounded. Other external inputs include the fuel rate and the engine speed. The states are : the intake manifold pressure and the burned gas rate.

III. MODELING

A model of the intake manifold based on a mean-value diesel engine model reported in [3] and [5] is derived to design the air path observer. In this model, the heat exchangers (intercooler and the EGR-cooler) are not included. The reason for this is that the temperatures downstream the heat exchangers are measured by the sensors. For the sake of simplicity we do not take into account the turbocharger dynamics. Nomenclature used in the model is presented in TABLE I.

A. Intake manifold modeling

Applying the first law of thermodynamics (energy conservation principle), by considering that the heat transfer to the surroundings is negligible, leads to the expression of the variation of the intake manifold pressure as a function of the aspirated flow D_{asp}, the manifold air flow D_{air} and the EGR flow D_{egr}. The manifold dynamics pressure P_{int} is described by the following equation:

$$\dot{P}_{\text{int}} = \frac{\gamma R}{V_{\text{int}}} \left(D_{air} T_{air} + D_{egr} T_{egr} - D_{asp} T_{\text{int}} \right) \tag{1}$$

where V_{int} is the manifold volume, R the perfect gas constant relative to the air, T_{air} is the air temperature, T_{int} is the temperature in the intake manifold and T_{egr} is the temperature of EGR gas-flow.

The aspirated flow is given by

$$D_{asp} = \eta_{vol} \left(N_e, \frac{P_{\text{int}}}{T_{\text{int}}} \right) \frac{P_{\text{int}}}{R T_{\text{int}}} V_{cyl} \frac{N_e}{120} \tag{2}$$

with V_{cyl} is the cylinders' volume. η_{vol} is the volumetric efficiency which is experimentally derived and eventually defined through a look-up table $\eta_{vol}\left(N_e, \frac{P_{\text{int}}}{T_{\text{int}}}\right)$. N_e is the engine speed.

The EGR mass flow is given by

$$D_{egr} = V_{egr} \frac{P_{exh}}{\sqrt{R T_{exh}}} \sigma \left(\frac{P_{\text{int}}}{P_{exh}} \right) \tag{3}$$

where V_{egr} is the opening area of EGR valve. The function $\sigma\left(\frac{P_{atm}}{P_{int}}\right)$ is given by

$$\sigma\left(\frac{P_{down}}{P_{up}}\right) = \begin{cases} \sqrt{\frac{2\gamma}{\gamma-1}\left\{\left(\frac{P_{down}}{P_{up}}\right)^{\frac{2}{\gamma}} - \left(\frac{P_{down}}{P_{up}}\right)^{\frac{\gamma+1}{\gamma}}\right\}} \\ if\ \left(\frac{P_{down}}{P_{up}}\right) \geq \left(\frac{P_{down}}{P_{up}}\right)^{\frac{\gamma}{\gamma-1}} \\ \sqrt{\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \quad otherwise, \end{cases} \tag{4}$$

where the subscripts "up" and "down" stand for upstream and downstream values across the opening area of EGR valve.

The dynamic of burned gas fraction in the intake manifold F_{int} is derived as

$$\dot{F}_{\text{int}} = \frac{R T_{\text{int}}}{P_{\text{int}} V_{\text{int}}} \left(D_{egr} \left(F_{exh} - F_{int} \right) - D_{air} F_{int} \right) \tag{5}$$

The Air/Fuel Ratio sensor located downstream the turbine allows us to obtain a reflection of the composition in the exhaust manifold F_{exh}. The composition of the EGR F_{egr} is that of the exhaust manifold F_{exh}, i.e. $F_{egr} = F_{exh}$ and $T_{egr} = T_{exh}$.

B. State space representation

Let us set $x_1 = P_{\text{int}}$, $x_2 = F_{\text{int}}$, $u_1 = D_{\text{air}}$, $u_2 = D_{\text{egr}}$ and note : $\alpha_{\text{int}} = \frac{\gamma R T_{\text{int}}}{V_{\text{int}}}$, $\alpha_{\text{air}} = \frac{\gamma R T_{\text{air}}}{V_{\text{int}}}$, $\alpha_{\text{egr}} = \frac{\gamma R T_{\text{egr}}}{V_{\text{int}}}$ and $\beta_{\text{int}} = \frac{1}{R T_{\text{int}}} V_{cyl} \frac{N_e}{120}$. The state space nonlinear model of the intake is obtained from Eq.(1) and Eq.(5). The considered output is $y = x_1$.

$$\begin{cases} \dot{x}_1(t) = -f_1(x_1)x_1 + \alpha_{air}u_1(t) + \alpha_{egr}u_2(t) \\ \dot{x}_2(t) = -f_2(x_1,u_1,u_2)x_2(t) + f_3(x_1)u_2(t) \end{cases} \tag{6}$$

The nonlinear functions are given by

$$\begin{aligned} f_1(x_1) &= \alpha_{\text{int}} \beta_{\text{int}} \eta_{vol} \left(N_e, \frac{P_{\text{int}}}{T_{\text{int}}} \right) \\ f_2(x_1,u_1,u_2) &= \frac{\alpha_{\text{int}}}{x_1}(u_1 + u_2) \\ f_3(x_1) &= \frac{\alpha_{\text{int}} F_{exh}}{x_1} \end{aligned}$$

Model (6) is nonlinear, thus a nonlinear observer has to be designed. One way to take into account the nonlinearities of the model is to use a polytopic approach such as the Takagi and Sugeno's modeling [8]. Since $x_1 \neq 0$, the functions f_1, f_2 and f_3 can be assumed to be bounded such that

$$\forall i \in \{1,2,3\}\ ,\ \underline{f_i} \leq f_i \leq \overline{f_i} \tag{7}$$

The representation (6) is one of many possible reformulations of the engine model. These will be subsequently used to derive a TS model using the sector nonlinearity approach [10].

Symb.	Quantity	Unit
M_{int}	Total mass in the i.m	Kg
$M_{int,air}$	Air mass in the i.m	Kg
P_{atm}	Atmospheric pressure	Pa
P_{int}	Pressure in the i.m	Pa
F_{int}	Fraction of burned gas in the i.m	$-$
F_{exh}	Fraction of burned gas in the e.m.	$-$
T_{int}	Temperature in the i.m	K
T_{air}	Temperature of air	K
T_{egr}	Temperature of EGR gas-flow into the i.m	K
D_{air}	Manifold air flow	$Kg.s^{-1}$
D_{egr}	EGR flow	$Kg.s^{-1}$
D_{asp}	Aspirated flow into the cylinders	$Kg.s^{-1}$
N_e	Engine speed	rpm
V_{int}	Volume of the i.m	m^3
V_{cyl}	Volume of the cylinders	m^3
R	Ideal Gas constant	$J.\left(KgK^{-1}\right)$
γ	Ratio of specific heats	$-$
η_{vol}	Volumetric efficiency	$-$
λ	Air/Fuel equivalence ratio	$-$

TABLE I

NOMENCLATURE. (I.M. REFERS TO THE INTAKE MANIFOLD)

C. TS fuzzy modeling

In order to design an observer through fuzzy approach to estimate the state, the nonlinear state model (6) has to be transformed into an equivalent TS fuzzy model [8]. A TS model is a nonlinear model composed of linear models blended together with some nonlinear functions. The purpose is to obtain an exact representation of a nonlinear model in a compact set of the state variables. The way to derive one TS model from a nonlinear model is to use two nonlinear functions (called membership functions in the TS model) to describe each nonlinearity. This systematic method, called the sector nonlinearity approach [10], results in a TS model with $r = 2^{n_l}$ linear models (rules), where n_l is the number of nonlinearities of the model. The TS model may be expressed under the following state space form

$$\begin{cases} \dot{x}(t) = \sum\limits_{i}^{r} h_i(z(t))\left(A_i x(t) + B_i u(t)\right) \\ y(t) = Cx(t) \end{cases} \tag{8}$$

where $x(t) \in \Re^2$ is the state vector, $u(t) \in \Re^2$ is the control input vector, $y(t) \in \Re$ is the output vector and $z(t)$ is called the premise vector. A_i, B_i and C are matrices with appropriate dimensions.

The nonlinear scalar functions $h_i(z(t))$ are assumed to be positive and to verify the convex sum property. To obtain these functions, each bounded function f can be easily split using two nonlinear functions $M_1(.) \geq 0$, $M_2(.) \geq 0$ such that $M_1(.) + M_2(.) = 1$ (see, [10]) as follows

$$f(.) = \underline{f}\frac{\overline{f} - f(.)}{\overline{f} - \underline{f}} + \overline{f}\frac{f(.) - \underline{f}}{\overline{f} - \underline{f}} = \underline{f}M_1(.) + \overline{f}M_2(.) \tag{9}$$

This so-called sector nonlinearity approach can be repeated for each nonlinear function of the model. Note that $z(t)$ is called the premise vector and it is assumed measurable vector.

By considering the nonlinear model (6), the constant matrices of the considered model (8) are given below

$$\begin{aligned} A_{i=\{1,2\}} &= \begin{bmatrix} -\overline{f_1} & 0 \\ 0 & -\overline{f_2} \end{bmatrix} \\ A_{i=\{3,4\}} &= \begin{bmatrix} -\overline{f_1} & 0 \\ 0 & -\underline{f_2} \end{bmatrix} \\ A_{i=\{5,6\}} &= \begin{bmatrix} -\underline{f_1} & 0 \\ 0 & -\overline{f}_2 \end{bmatrix} \\ A_{i=\{7,8\}} &= \begin{bmatrix} -\underline{f_1} & 0 \\ 0 & -\underline{f_2} \end{bmatrix} \end{aligned}$$

$$\begin{aligned} B_{i=\{1,3,5,7\}} &= \begin{bmatrix} \alpha_{\text{air}} & \alpha_{\text{egr}} \\ 0 & \overline{f_3} \end{bmatrix} \\ B_{i=\{2,4,6,8\}} &= \begin{bmatrix} \alpha_{\text{air}} & \alpha_{\text{egr}} \\ 0 & \underline{f_3} \end{bmatrix} \end{aligned}$$

$$C = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

IV. AIR PATH OBSERVER

A. *Preliminaries*

Autonomous Fuzzy Systems : Consider the autonomous fuzzy system

$$\dot{x}(t) = \sum_{i=1}^{r} \mu_i(\xi(t)) A_i x(t) \tag{10}$$

For system (10), several stability conditions have been derived. Among them, a well-known and frequently used condition is formulated below as in [9].

Theorem 1. System (10) is asymptotically stable if there exists $P = P^T > 0$ so that $PA_i + A_i^T P < 0$ for $i = 1, 2, \ldots, r$.

B. *Observer design*

Consider the following observer for system (8)

$$\begin{cases} \dot{\hat{x}}(t) = \sum\limits_{i}^{r} h_i(z(t))\left(A_i \hat{x}(t) + B_i u(t) + K_i\left(y(t) - C\hat{x}(t)\right)\right) \\ \hat{y}(t) = C\hat{x}(t) \end{cases} \tag{11}$$

The error system equations in terms of the error variable: $\tilde{x}(t) = x(t) - \hat{x}(t)$ is

$$\dot{\tilde{x}}(t) = \sum_{i}^{r} h_i(z(t))\left(A_i - K_i C\right)\tilde{x}(t) \tag{12}$$

Theorem 1 can be applied in order to design the observer. The estimation error using the observer (11) is asymptotically stable if there exist $P = P^T > 0$ and K_i for $i = 1, 2, \ldots, r$ such that

$$P\left(A_i - K_i C\right) + \left(A_i - K_i C\right)^T P < 0 \tag{13}$$

Inequality (13) can be written as

$$PA_i + A_i^T P - C^T K_i^T P - PK_i C < 0 \quad \forall i \in \{1, \ldots, r\} \tag{14}$$

The presence of the terms PK_i, makes the inequality (14) nonlinear. To linearize it, let us define the following change of variable $F_i = PK_i$. The inequality (14) can then be written as

$$PA_i + A_i^T P - F_i C - C^T F_i^T < 0 \quad \forall i \in \{1, \ldots, r\} \tag{15}$$

By solving the LMI (15), we obtain the matrices P and F_i. The gains matrices K_i can then be deduced as follow : $K_i = P^{-1}F_i$.

V. A DEVELOPED CONTROLLER FOR THE AIR PATH DYNAMIC SYSTEM

The proposed global control scheme is described in Fig.2. The air path observer, described in Section IV, provides an estimation of the fraction of burned gas in the intake manifold F_{int}.

By taking into account the gear-box configuration, the position of the accelerator fixed by the driver is turned into a torque control objective under the form of an IMEP set point. Then, the set points for the intake manifold pressure and the BGR are inversely given by experimentally calibrated static maps on the ($IMEP_{ref}$,N_e) operating range. The engine speed N_e is considered as external input. The set points vector is defined as

$$\begin{aligned} P_{\text{int},ref} &= f_{pressure}\left(IMEP_{ref}, N_e\right) \\ F_{\text{int},ref} &= f_{BGR}\left(IMEP_{ref}, N_e\right) \end{aligned}$$

Now, we have to design a multivariate control (using the EGR valve and the VGT as actuators) of the masses to reach the set points given by the torque controller by applying the Recursive Model Free Control (RMFC) as described below. Then, the outputs of the RMFC component ($D_{egr,ref}$ and $D_{air,ref}$) are used to determine the opening area of the EGR valve (V_{egr}) and the VGT position (V_{tur}). PIDs controllers are added to the structure in order to provide further accuracy and robustness.

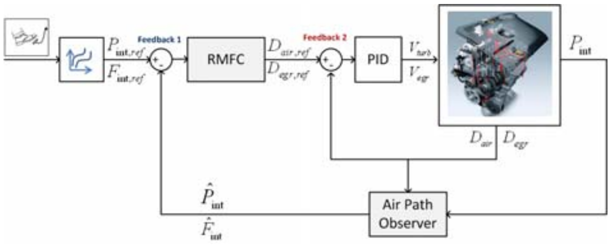

Fig. 2. A controller for the air path dynamic system

The goal of the second feedback is to control D_{egr} and D_{air} toward the feasible references set points $D_{egr,ref}$ and $D_{air,ref}$ obtained by the RMFC controller. The main purpose of the first feedback is to give a feasible and continuous set points for the second feedback action (see Fig 2).

A. Recursive Model Free Controller

The used RMFC is developed by using hybrid systems called Piecewise Continuous Systems (PCS) which are characterized by autonomous switchings and controlled impulses [6]. Thus, based on PCS theory, a Piecewise Continuous Controller (PCC) was firstly developed, enabling sampled trajectory tracking of linear systems by undertaking a continuous time state feedback or a delayed and sampled output feedback. Then for an improved tracking performance, a Derived PCC (DPCC) with shorter sampling period close to zero was derived in [12]. The referred RMFC which is derived from the DPCC is defined in the equation (16). Note that $\lambda(t^+)$ is the function λ at the given instant $t+t_e$ when the constant switching period t_e is close to zero. The equation (16) can be interpreted algorithmically as an iterative evaluation of $\lambda(t)$ at each calculation step.

$$\begin{cases} \lambda(t^+) = \|e(t)\|_2 e(t) + \xi(t)\lambda(t) \\ u(t) = C_c \lambda(t) \end{cases} \tag{16}$$

where $\lambda(t) \in \Re^2$ is the RMFC state, $e(t) = \begin{bmatrix} P_{int,ref} \\ F_{int,ref} \end{bmatrix} - \begin{bmatrix} P_{int} \\ \hat{F}_{int} \end{bmatrix} \in \Re^2$ is the system output trajectory tracking error, $C_c > 0 \in \Re^{2\times 2}$ is the RMFC output matrix, and $\xi(t)$ is the component trajectory tracking coefficient.

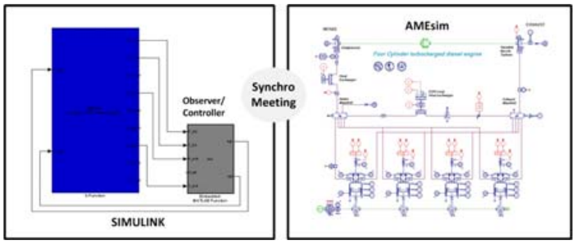

Fig. 3. AMESim/SIMULINK co-simulation platform

To realize $e(t) \to 0$, the value of $\xi(t)$ is tuned as:

$$\xi(t) = \exp\left(\frac{-e(t)^T e(t)}{2\sigma^2}\right) \tag{17}$$

with $0 < \sigma \leq 1$. Thus the knowledge of the plant parameters is not necessary.

Besides, according to [13], the proposed RMFC can be approximately written as

$$u(t) \approx \frac{2C_c\sigma^2}{\|e(t)\|_2} e(t). \tag{18}$$

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Note that, F_{int} is not measured. Its estimation $\hat{F}_{int}$ is used.

VI. MODEL IN THE LOOP : RESULTS

The developed controller has been tested on a four-cylinder diesel engine model running on AMEsim® platform in co-simulation with SIMULINK (Fig.3). The simulation is performed considering engine running at 3000 RPM and variable torque demand in HCCI combustion mode, i.e, each set points kept for 10 seconds. Fig 4, 5, 6 and 7 show experimental closed-loop results using the co-simulation environment.

Fig.4 and Fig.5 show respectively the intake manifold pressure and the BGR histories : Dashed set points, solid closed-loop given by AMEsim. Fig.6 and Fig.7 show the flows histories : Dashed set points given by the RMFC controller, solid closed-loop given by AMEsim. The proposed strategy show good performance in term of static state error with an accepted setting time. Note that in diesel engine, the air path dynamic is very slow compared to that of the fuel path and the torque control is firstly done via the fuel path. After, in order to optimize the combustion, we have to control the air path. Therefore the setting time obtained by the proposed strategy is accepted.

VII. CONCLUSION

In this paper, we proposed a new control strategy based on Recursive Model Free Controller (RMFC). The proposed strategy is successfully evaluated using a professional advanced diesel engine simulator AMEsim(LMS) platform in co-simulation with SIMULINK. The proposed strategy has shown good performance in term of static state error with an accepted setting time. Due to its implementation simplicity, this strategy has the potential to be used on real-time system control which would be the subject of our future effort.

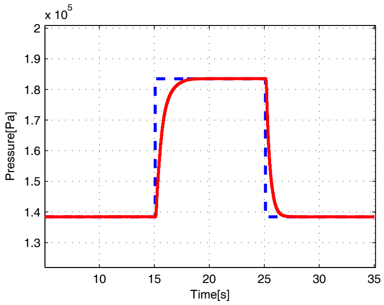

Fig. 4. AMEsim results : IMEP transient from 8 bar to 14 bar and then to 8 bar at 3000 RPM. Intake manifold Pressure histories, Dashed : set point, solid : closed-loop

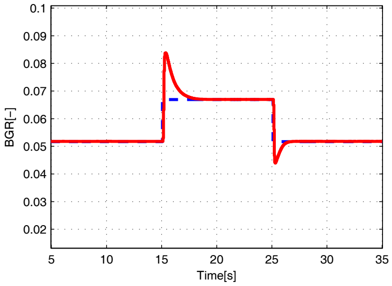

Fig. 5. AMEsim results : IMEP transient from 8 bar to 14 bar and then to 8 bar at 3000 RPM. BGR histories. Dashed : set point, solid : closed-loop

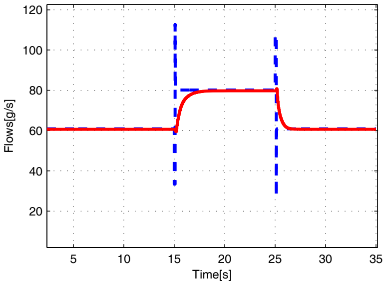

Fig. 6. AMEsim results : IMEP transient from 8 bar to 14 bar and then to 8 bar at 3000 RPM. Air flow histories (D_{air}). Dashed : set point, solid : closed-loop

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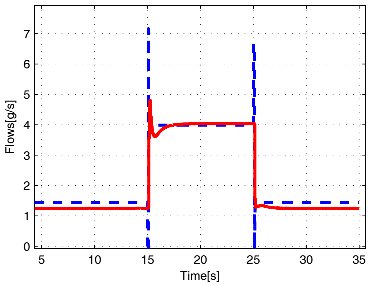

Fig. 7. AMEsim results : IMEP transient from 8 bar to 14 bar and then to 8 bar at 3000 RPM. EGR flow histories (D_{egr}). Dashed : set point, solid : closed-loop

REFERENCES

[1] M. Ammann, L. Guzzela N. Fekete, and A. Glatfelder. Model-based control of the vgt and egr in a turbocharged common-rail diesle engine: theory and passenger car implementation. In *Proc . of the SAE Conference. number 2003-01-0357*, 2003.

[2] J. Chauvin, G. Corde, N. petit, and P. Rouchon. Experimental motion planing in air path control for hcci engine. In *Proc. of the American Control Conference*, 2006.

[3] M. Jankovic and I. Kolmanovsky. Constructive lyapounov control design for turbocharged diesel engines. *IEEE Transactions on Control Systems Technology*, 8:288–299, 2000.

[4] M. Jung and K. Glover. Comparaison of uncertainty parametrisation for h-infinity robust control of turbocharged diesel engines. *Proc. of Control Engineering Practice*, 13:15–25, 2005.

[5] K. kao and J. Moskwa. Turbocharged diesel engine modeling for nonlinear engine control and state estimation. *ASME Journal of Dynamic Systems, Measurement and Control*, 117(1):20–30, 1995.

[6] V. Koncar and C. Vasseur. Control of linear systems using piecewise continuous systems. *IEE Control Theory & Applications*, 150(6):565–576, Nov. 2003.

[7] A. Stefanopoulou, I. Kolmanovsky, and J. Freudenberg. Control of variable geometry turbocharged diesel engines for reduced emissions. *IEEE Transactions on Control Systems Technology*, 8:733–745, 2000.

[8] T. Takagi and M. Sugeno. Fuzzy identification of systems and its applications to modeling and control. *IEEE Transactions on Systems, Man and Cybernetics,*, 15(1):116–132, 19985.

[9] K. Tanaka, T. Ikeda, and H. Wang. Fuzzy regulators and fuzzy observers: re-laxed stability conditions and lmi-based designs. *IEEE Transactions on Fuzzy Systems*, 6(2):250–265, 1998.

[10] K. Tanaka and H. O. Wang. Fuzzy control systems design and analysis: A linear matrix inequality approach. In *New York: Wiley, Wiley-Interscience, ISBN 0-471-32324-190000.*, 2001.

[11] M. van Nieuwstadt, I. Kolmanovsky, P. Moraal, A. Stefano oulou, and M. jankovi. Experimental comparaison of egr-vgt control schemes for a high speed diesel engine. *Proc. of the IEEE Control Systems Magazine*, 20:63–79, 2000.

[12] H.P. Wang, C. Vasseur, and V. Koncar. Piecewise continuous systems used in trajectory tracking of a vision based x-y robot. In *Novel Algorithms and Techniques In Telecommunications, Automation and Industrial Electronics*, pages 255–260. Springer Netherlands, 2008.

[13] H.P. Wang, C. Vasseur, V. Koncar, and N. Christov. Recursive model free controller used in mimo nonlinear system's trajectory tracking. In *18th Mediterranean Conference on Control and Automation*, pages 436 – 441, Marrakech, Morocco, June 2010.

[14] X. Wei and L. Del Re. Gain scheduled hinf control for airpath systems of deisel engines using lpv techniques. *IEEE Transaction on Control Systems Technology*, 15(3):406–415, 2007.