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Air-Fuel ratio estimation along Diesel engine transient operation using in-cylinder pressure

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Abstract

The increasing competition among automotive OEMs together with the worsening of the environmental pollution has lead to the development of complex engine systems. Innovative control strategies are needed to simplify and improve the Engine Management System (EMS), moving towards energy saving and complying with the restrictions on emissions standards. In this scenario the application of methodologies based on the in-cylinder pressure measurement finds widespread applications. Indeed, the in-cylinder pressure signal provides direct in-cylinder information with a high dynamical potentiality that is fundamental for the control and diagnosis of the combustion process. Furthermore, the in-cylinder pressure measurement may also allow reducing the number of existing sensors on-board, thus lowering the equipment costs and the engine wiring complexity.
The paper focuses on the estimation of the Air-Fuel ratio from the in-cylinder pressure signal. The methodology is based on the analysis of the statistical moments of the pressure cycle and was already presented by the authors and applied to a set of steady state engine operation conditions. In this paper the technique has been enhanced in order to be applied under the more critical engine transient operation. The results achieved show a satisfactory accuracy in predicting the Air-Fuel ratio during engine transients performed at the engine test bench on a Common-Rail turbocharged Diesel engine.

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Keywords: In-cylinder pressure; air-fuel ratio; diesel engine; combustion control.

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1. Introduction

Recently many complex engine subsystems and control technologies have been introduced to meet the demands of strict regulations and the competitive market too. Anyway, for diesel engines, combustion control is one of the most effective approaches for reducing not only engine exhaust emissions but also cylinder-by-cylinder variation and engine consumption, because of the large amount of control variables to be managed. For these reasons, innovative control strategies appear as the best solution for vehicle manufacturers in order to achieve cleaner and energy saving engines. With this aim a large number of actuators and sensors are used, both in steady-state and transient operations, in order to monitor engine states and outputs. Otherwise most of information provided by the sensors can be extracted from the in-cylinder pressure trace.

Studies about the 'Pressure-Based' Control (PBC) started since the sixties, but the first application in commercial cars was only between 1980 and 1990 [1] . The reader is addressed to Powell [2] , who was the first author to propose a pressure-based algorithm for the estimation of the air-fuel ratio and misfire detection on spark ignition engines. In 1995 Leonhardt implemented a closed loop control on the injection pattern [3] , by means of a neural network based on specific combustion metrics extracted from the pressure cycle. In 1999 Tunestal instead [4] , improved the cold start on Diesel engine and Mladek, one year later, developed an innovative technique for the estimation of the in-cylinder trapped mass [5] . More recently the application of pressure based methodologies has been oriented to Diesel engine control for virtual sensing of NO_x and PM emissions [6] [7] .

This work focuses on the estimation of the air-fuel ratio in a Common-Rail turbocharged Diesel engine based on the statistical moments of in-cylinder pressure cycle. The in-cylinder AFR estimation allows improving the closed-loop control of the injection pattern and the air path, with benefits on engine emissions and fuel consumption especially during cold starts and transient operations. Indeed, the in-cylinder AFR estimation allows avoiding the gas inertia effects and the time delay that typically affect the measurement provided by the UEGO sensor. The technique has been already presented and applied by the authors on two different automotive Diesel engines, by processing the in-cylinder measurements collected in steady-state conditions [8], [9] . In the current study, the technique has been enhanced to be applied under engine transient operations that are of course of greater interest to test the feasibility of the on-board application. Suitable procedures have been introduced to improve model identification by processing the raw pressure measurements and by detecting the parameters that are mostly correlated to the AFR.

Nomenclature

a_n, b_n	n-th regression constant [/]
AFR	Air-Fuel ratio [/]
ATDC	After Top Dead Centre [deg]
CAD	Crank Angle Degree [deg]
EGR	Exhaust Gas Recirculation
EMS	Engine Management System
EOC	End of Combustion [deg]
m	Polytropic index in non-adiabatic condition [-]
M_{nn}	Normalized statistical moment of order n
N	Engine speed [rpm]
$p(\theta)$	In-cylinder pressure [bar]
PBC	Pressure-Based Control
R2	Correlation index [/]
SOI	Start of Injection [deg]
TDC	Top Dead Centre
V	Actual displaced volume [m3]
VGT	Variable Geometry Turbine
θ_c	Centroid crank angle [deg]

2. Experimental Set-up

The techniques were developed and validated with respect to experimental data collected in transient conditions at the engine test bench at University of Salerno. The reference engine is a four cylinders turbocharged Common-rail Diesel engine equipped with VGT, whose main technical data are listed in Table 1.

Table 1. Technical data of the reference engine

Cycle	4 strokes Diesel
Cylinder [#]	4 in-line
Displacement [cm^3]	2300
Compression ratio [/]	16.2:1
Bore x stroke [mm]	88 x 94
Max Power [kW]	107 @ 3600 rpm
Max Torque [Nm]	350 @ 1500 rpm
Rail Pressure [bar]	1600

The experimental data set was composed of two transients, characterized by both smooth and sharp load variations, shown in Fig. 1. The engine speed was ranging from 1250 rpm up to 2500 rpm, the brake torque from 80 up to 250 Nm and the EGR from 0 up to 40%. The in-cylinder pressure was measured with a sampling period of 0.2 crank angle degree (CAD) by a piezo-electric transducer, with sensitivity equal to 16 pc/bar, located in a glow-plug adaptor. The main I/O Engine Management System (EMS) variables were monitored and acquired by an Etas INCA system. The AFR was measured by an UEGO sensor with accuracy ±0.7%, located downstream the turbine.

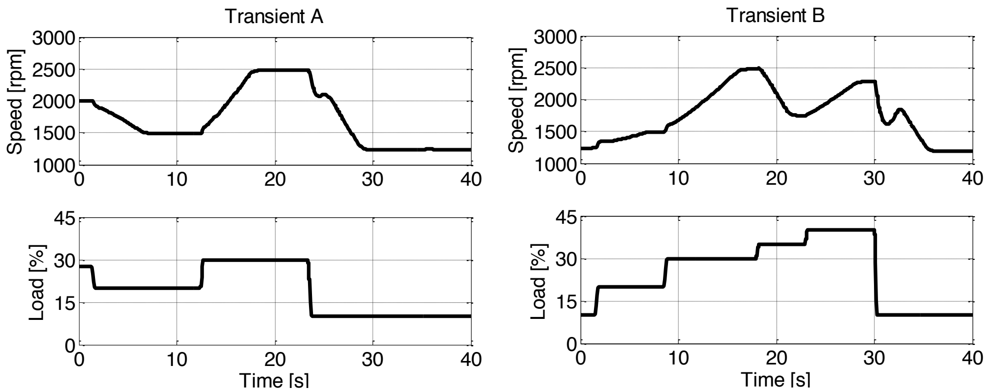

Fig. 1. Sequence of dynamometer operation on the test engine. Identification (A) and Validation (B) transient.

It's worth noting that, due to the UEGO sensor location, there is a significant time lag between the measured AFR signal and the corresponding estimation, based on the cylinder pressure measurement. Therefore a suitable post-processing of the raw pressure measurement was carried out to remove such variable delay during both identification and validation processes. Particularly, the time lags were calculated in the events corresponding to the five load steps of transient B, by assuming the experimental indicated mean effective pressure (IMEP) as trigger for the UEGO signal. Afterwards, a black-box model was developed considering the variables that mostly affect the delay between the two signals, namely exhaust pressure and temperature, engine and turbo speed, VGT and EGR valve position. It's worth noting that all these variables are usually available from commercial ECU. The delay model was successively applied to the whole transient, according to the different engine working conditions along it.

3. Methodology

The proposed technique compares the in-cylinder pressure trace to a Gaussian statistical distribution around the top dead center (TDC) in the pressure-crank angle plan, in order to use proper statistical indexes for the characterization of the pressure shape. Since the AFR value affects the combustion durations and pressure peak as well, different in-cylinder pressure distributions with respect to its centroid are expected by varying the AFR. Therefore this latter results strongly correlated with the statistical moments, particularly, the 2nd and 3rd order central moments are related to the spread (i.e. variance) and symmetry (i.e. skewness) of $p(\theta)$ with respect to θ_c [11] . The 4th order central moment corresponds to the Kurtosis index and is related to the sample distribution around the mean value.

The central moments are computed by bounding the cylinder pressure trace within the start of injection (SOI) and the end of combustion (EOC), in order to focus the effects of the AFR on the combustion process. Furthermore, in order to limit the influence of the poor sensor accuracy at low pressure [12] , the central moments are normalized by the area of the motoring pressure:

$$M_{nn} = \frac{\int_{\theta_1}^{\theta_2} (\theta - \theta_c)^n \, p(\theta) \, d\theta}{\int_{\theta_1}^{\theta_2} p_{motored}(\theta) \, d\theta} \tag{1}$$

where the centroid crank angle was calculated as the ratio between the first and the zero order statistical moment ($\theta_c = M_1/M_0$); the pressure cycle in motored condition was calculated by the polytropic relationship and the polytropic exponent was identified minimizing the mean square error between the measured pressure trace and the calculated one, in order to avoid affections by the heat transfer. In the previous works [8] , [9] , θ_1 and θ_2 were assumed respectively as the instants at 2% (θ_{SOC}) and 98% (θ_{EOC}) of the whole combustion process and were selected from the heat release rate profile, as depicted in Fig. 2 (a). On the other hand, for the current study, the impact of the reference angles on the correlation between statistical moments and AFR was analyzed. Fig. 3 shows that the best results are achieved by considering the reference interval as constant for all the operating conditions (θ_1=-50 - θ_2=100), as depicted in Fig. 2 *(b)*). This result can be explained considering that the statistical moments become more strictly related to the cylinder pressure shape and less influenced by combustion timing. Particularly, in Fig. 3 (a) at least three clusters with a well-defined trend can be appreciated, corresponding to the three engine speed steps reached during the transient A.

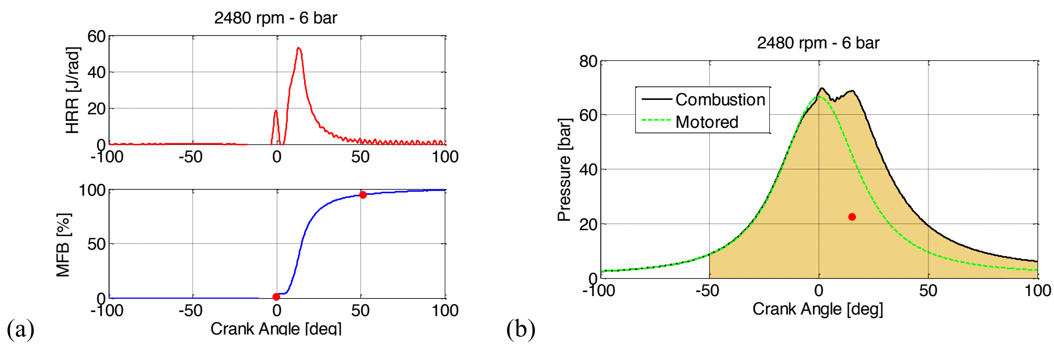

Fig. 2. (a): Heat release rate (upper) and fuel burned fraction (lower) vs. crank angle at Speed = 2480 rpm and BMEP = 6 bar during transient A. (b): Corresponding cylinder pressure traces in combustion (black solid line) and motored (green dashed line) condition.

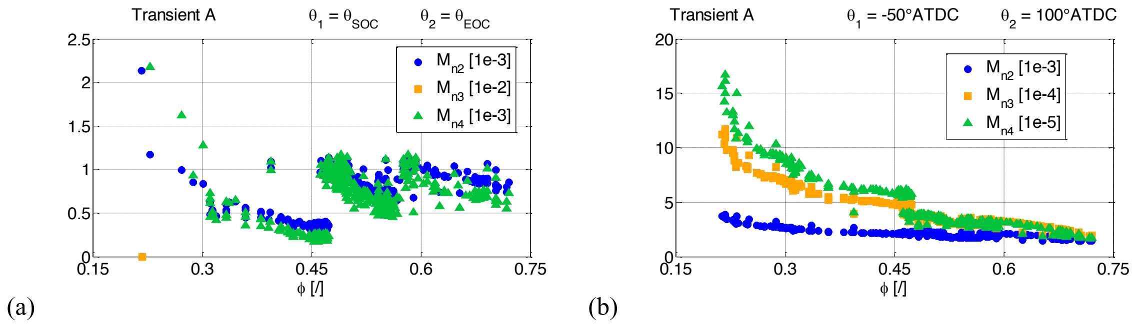

Fig. 3. Trends of the second, third and fourth central moments vs. the equivalence ratio at different reference intervals. Transient A.

Despite the better correlations evidenced in Fig. 3, the results achieved by estimating the AFR from the sole statistical moments were not satisfactory enough. A new independent variable was then considered by introducing the indicated mean effective pressure *(imep)* that actually allows taking into account the speed and load time histories:

$$X_{afr} = \left(M_{n2}\right)^{a_1} \cdot \left(M_{n3}\right)^{a_2} \cdot \left(M_{n4}\right)^{a_3} \cdot \left(imep\right)^{a_4} \tag{2}$$

where M_{nn} are the normalized moments of order n. The exponents a_n were identified by means of an optimization algorithm to find the maximum correlation between X_{afr} and the measured AFR along the transient A. Particularly, all the descriptors in X_{afr} were normalized at the same size order (as shown in Fig. 3) and the corresponding coefficient values are: a_1=-10.4, a_2=42.1, a_3=-28.5, a_4=-1.5. Once the coefficients a_n are known, a black-box model expressing AFR as function of X_{afr} was developed:

$$\overline{AFR} = b_0 + b_1 \cdot X_{afr} \tag{3}$$

The parameters identification (b_n) was carried out by means of an ordinary least squares method with the following results: b_0=20.05 and b_1=0.55.

Fig. 4 shows the measured (black dots) and estimated (green line) AFR vs. the variable X_{afr}, along the transient A considered for model identification. The boundary red lines correspond to the 95% of confidence intervals.

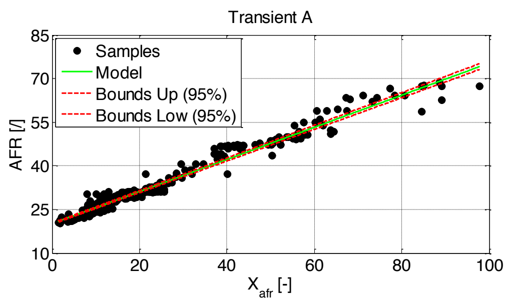

Fig. 4. Measured and estimated AFR vs. X_{afr}.

4. Results

Fig. 5 show the comparison between measured and predicted AFR, along both identification (A) and validation transients (B). In the former case (i.e. A), the model exhibits a very good accuracy, confirmed by a correlation coefficient R^2 equal to 0.98. Fig. 6 shows the relative error distribution for the two transients A and B.

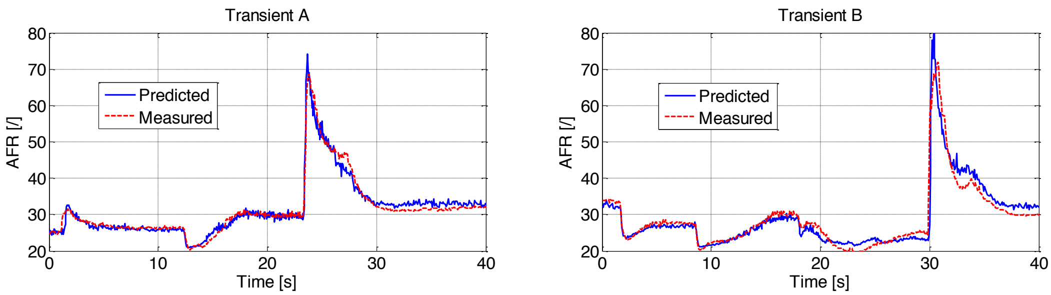

Fig. 5. Comparison between measured and predicted AFR for the identification transient (A) and the validation transient (B).

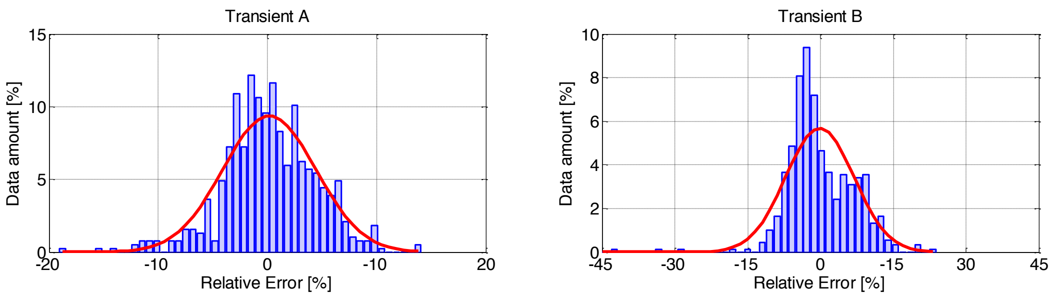

Fig. 6. Relative error distribution between estimated and measured AFR.

The results achieved for the validation transient B, shown in Fig. 5 (b), confirm the good model accuracy, with a correlation index equal to 0.96. The figure evidences that the model can track with accuracy the measured signal except for the load steps that takes place at approx. 33s. Indeed, in case of very fast and sharp transients the in-cylinder pressure measurement could lack in accuracy and consequently the AFR estimation becomes critical. Nevertheless it is worth noting that this specific maneuver corresponds to a tip-out with presumable fuel cut-off, that is not critical for emissions control.

5. Conclusions

A methodology for the AFR estimation based on the in-cylinder pressure processing has been presented. The technique is based on the statistical moments of the pressure cycle and has been applied to predict the AFR along engine transients performed at the test bench on an automotive Common-Rail Diesel engine. The results show that the proposed methodology allows tracking the measured AFR with a good agreement, with a correlation index between measured and predicted data equal to 0.98 and 0.96 for the two transients carried out for model identification and validation, respectively.

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