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# Methodologies for Air-Fuel ratio and trapped mass estimation in Diesel engines using the in-cylinder pressure measurement.

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**Abstract**

Nowadays the increasing automotive market competition together with the worsening of the environmental pollution leaded 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 engines 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 an 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.

This paper focuses on the detection of the Air-Fuel ratio and the in-cylinder trapped mass after the intake valve closing from the in-cylinder pressure signal. The Air-fuel ratio estimation might allow replacing the lambda sensor, the estimation method is based on a statistical approach. The in-cylinder trapped mass estimation gives the opportunity to by-pass the CO2 measurement for the evaluation of the EGR rate, in this case the Δp method is proposed. The developed techniques were validated vs. experimental data measured at the engine test bench on a Common-Rail turbocharged Diesel engine. The results show a good accuracy in predicting Air-Fuel ratio and in-cylinder trapped mass in a wide engine operating range. Because of both the low computational burden and the good results, these methodologies are suitable to be implemented on-board.


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*Keywords: In-cylinder pressur; air-fuel ratio; trapped mass; diesel engine.*

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**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 [-] |
| $m_{ivc}$ | In-cylinder trapped mass [mg/str] |
| $m_f$ | Fuel mass [mg/str] |
| $M_{nn}$ | Normalized statistical moment of order n |
| $N$ | Engine speed [rpm] |
| $p(\theta)$ | In-cylinder pressure [bar] |
| $p_{man}$ | Intake manifold pressure [bar] |
| PBC | Pressure-Based Control |
| R | Universal gas constant [J/kg/K] |
| $R^2$ | Correlation index [/] |
| SOI | Start of Injection [deg] |
| $T$ | Temperature [K] |
| TDC | Top Dead Centre |
| $V$ | Actual displaced volume [$m^3$] |
| VGT | Variable Geometry Turbine |
| $\theta_c$ | Centroid crank angle [deg] |

## 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 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] ).

In this work two different techniques are presented for the estimation of the air-fuel ratio and the in-cylinder trapped mass on an heavy-duty Diesel engines starting from the in-cylinder pressure measurement. The AFR estimation improves the closed-loop control on the injection pattern and on the air path, with the aim to respect the emissions target without penalizing the performance, to manage cold starts and transient operations. The proposed technique allow to estimate the AFR avoiding the gas inertia effects and so the time delay that typically affect the measurement provided by the UEGO sensor. Furthermore, the authors propose a methodology to estimate the in-cylinder trapped mass from the in-cylinder pressure cycle, with the purpose to replace the existing air flow sensor or to work jointly with it in order to estimate the EGR rate. These two technique have already been discussed and validated for a light-duty Diesel engine application ([8] .Therefore with the current application higher air mass and different in-cylinder pressure shapes are attended, due to completely different cylinders volume and injection pattern. Nevertheless the flexibility of both the two proposed methodologies is highlighted in this paper, by means little changes in the fundamental relationships proposed in the previous work ([8]

## 2. Experimental Set-up

The models have been developed and validated with respect to experimental data collected in steady state conditions at the engine test bench at University of Salerno. The reference engine is a four cylinders turbocharged Diesel engine equipped with VGT, whose main technical data are listed in Table 1. The engine is equipped with a Common-rail injection system and is designed for heavy-duty vehicles.

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 96 operating conditions, ranging from partial to full load without EGR, with engine speed variable from 1250 rpm up to 3000 rpm and brake torque from80 up to 300 Nm. 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.

## 3. Air-Fuel Ratio

The AFR estimation is important to carry out closed-loop control of fuel injection pattern and air path (i.e. VGT). Currently it is measured by a UEGO sensor located in the exhaust manifold, involving pure time delay due to gas transport from exhaust valve to sensor location ([9] ). The in-cylinder pressure cycle instead, allow to get an indirect but instantaneous measure of the AFR, avoiding this drawback and the UEGO sensor light-off during the cold starts too.

### *3.1. 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 2$^{nd}$ and 3$^{rd}$ order central moments are related to the spread (i.e. variance) and symmetry (i.e. skewness) of $p(\theta)$ with respect to $\theta_c$ ([10] ). The 4$^{th}$ 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 point out the effects of the AFR on combustion and hence on the in-cylinder trace. Furthermore, with the aim to reduce the effect of sensor scale factor errors ([11] ), the central moments are normalized by the area of the motoring pressure:

$$M_{nn} = \frac{\int_{\theta_{SOI}}^{\theta_{EOC}} \left(\theta - \theta_c\right)^n p(\theta) d\theta}{\int_{\theta_{SOI}}^{\theta_{EOC}} p_{motored}(\theta) d\theta} \tag{1}$$

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; $\theta_{SOI}$ and $\theta_{EOC}$were assumed respectively as the instants at 5% and 95% of the whole combustion process and were selected on the heat release rate profile.

Because of its complexity, the reference engine does not allow to establish a simply relationship between AFR and statistical moments only. Therefore, with the aim to define the engine variables and the statistical moment that mostly affect the AFR, a stepwise procedure was implemented, leading to the following relationship:

$$AFR = a_0 + a_1 \frac{{M_{4n}}^3}{M_{2n}} + a_2 \frac{{M_{4n}}^3}{M_{3n}} + a_3 \frac{1}{\sqrt{p_{man} M_{3n}}} \tag{2}$$

Where $M_{nn}$ are the normalized moments of order $n$, $p_{man}$ is the manifold pressure instead. The coefficients $a_n$ were identified by a Least Square Technique over the set of data depicted in Figure 1.

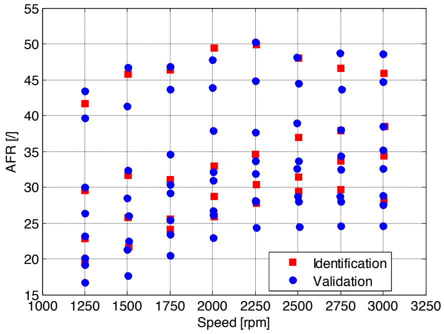


Fig. 1. Operating conditions investigated for the reference engine. The EGR has been deactivated in all conditions.

### 3.2. Results

In Figure 2 and Figure 3the results both for identification and validation test cases of the proposed techniqueare presented. Particularly, the Figure 2depicts the comparison between predicted and measured AFR, the model accuracy is appreciable on the graph by the store of data around the bisector, andis summarized by an high correlation coefficient equal to 0.98. The Figure 3confirms the agreement between estimated and measured AFR by showing the absolute error distribution.

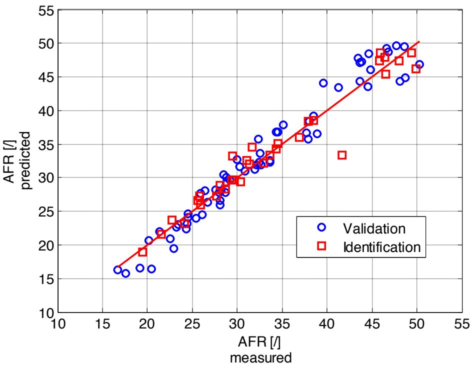


Fig. 2. Predicted vs. measured AFR for the identification and validation data sets. $R^2$=0.977.

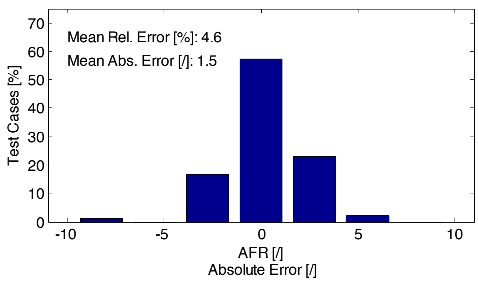


Fig. 3. Absolute error distribution between estimated and measured AFR.

## 4. In-Cylinder trapped mass

The in-cylinder trapped mass considered in this paper, includes the fresh air coming from the compressor, the internal and the external EGR rate trapped into the cylinder after the intake valve closing. In Diesel engines, the amount of in-cylinder trapped mass affect the combustion process and after-treatment devices as well, therefore its estimation is important to perform a suitable control of the turbocharger, the EGR actuator and the valve timing too. Currently this estimation is carried out by coupling the air mass flow sensor measurement and the EGR valve position.

### 4.1. Methodology

Starting from the work of Desantes et al. ([12] ), the in-cylinder trapped mass is estimated by means the pressure rise (*Δp*) between two pointsof the compression phase.

The in-cylinder trapped mass is expressed as function of the measured *Δp*by the following equation:

$$m_{ivc} = \frac{\Delta p V_a}{R T_a}\left(\left(\frac{V_a}{V_b}\right)^m - 1\right)^{-1} \tag{3}$$

Where$m$ is the non-adiabatic polytropic index, $R$ is the universal gas constant,$V_a$ and $V_b$ are the in-cylinder volumes at two different instants of the compression phase (named *'a'* and *'b'*),$T_a$ is the in-cylinder temperature at the first compression point considered *'a'*. Particularly, this latter was fixed at -70°ATDC, whilethe point *'b'* was assumed -50°ATDC. This choice was based on the need to avoid the pressure noise coming from the intake valve closing and the injection process as well.Equation ( 3 comes from the ideal gas law and polytropic law matching. Further detail can be found in [8] .

Since the in-cylinder temperature $T_a$ is the only unknown variable in equation ( 3, a black-box model expressing $T_a$as function of the available engine variables is needed for the air mass evaluation. $T_a$ depends on the heat transfer and the pressure rise, which are obviously related to the specific operating condition.Therefore the following model equation, dependent on the engine speed ($N$) and the injected fuel mass ($m_f$), was developed:

$$T_a = b_0 + b_1 m_f^{\,3} + b_2 \frac{N}{m_f} + b_3 N^2 m_f \tag{4}$$

The coefficients $b_n$ were identified by a Least Square Technique between reference and predicted in-cylinder temperatures at point *'a'*, over the set of data depicted with a red square in Figure 4.

Precisely, as the experimental in-cylinder temperature was not available, the reference temperature $T_a$, considered for model identification and validation, was calculated by inverting the equation ( 3. The reference experimental in-cylinder trapped mass $m_{ivc}$ is simply given by the air-flow meter measurements. Indeed, the effect of residual gas fraction and backflow were not considered, because of their negligible contribution, the external EGR was totally deactivated instead.With the EGR circuit activated, the proposed methodology would provide the overall amount of air and EGR mass. To discriminate the two contribution at least one measurement is required, typically the air-flow meter is employed in this case to calculate the EGR mass.

It's worth noting that differently from Desantes, a simplified law is proposed, based on a reduced number of engine variables involved.

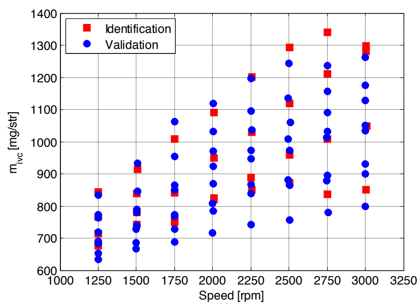


Fig. 4. Operating conditions investigated for the reference engine. The EGR has been deactivated in all conditions.

### 4.2. Results

Predicted and measured in-cylinder trapped massare comparedin Figure 5, both for identification and validation adopted test cases. The results exhibit very good model accuracy in estimating the in-cylinder trapped mass, with an overall correlation index $R^2$ equal to 0.996. The Figure 6shows the distribution of the absolute error between predicted and experimental trapped mass, which exhibits mean absolute and relative errors equal to 14.2 mg and 1.6 %, respectively.

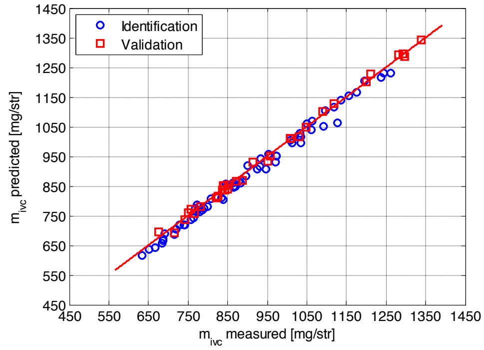


Fig. 5. Predicted vs. measured in-cylinder trapped mass for the identification and validation data sets. $R^2$=0.996.

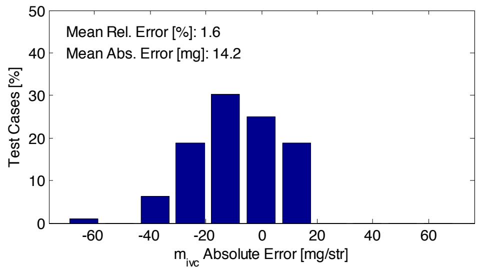


Fig. 6. Absolute error distribution between estimated and measured in-cylinder trapped mass.

## 5. Conclusions

Two methodologies for the estimation of AFR and in-cylinder trapped mass have been proposed, both based on the in-cylinder pressure processing. Identification and validation were carried out with two different experimental dataset, collected at the test bench of the University of Salerno, for an heavy duty Diesel engine. The results show a good agreement between experimental and calculated data, both for AFR and intake mass, with respectively 4.6% and 1.6% mean relative errors. The accuracy obtained with this mathematical models, and their low computational burden, make them suitable for on-board applications.

The pressure-based control allow to replace the air-flow meter and the lambda sensor in this case, but generally many other engine variables can be detected from the pressure signal, with reduced costs and system complexity. On the other hand, because of an indirect measurement, fast algorithms and high quality sensors are needed to guarantee reliable closed-loop control and precise measurements in a non-comfortable environment.

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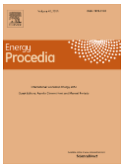


**Biography**

Rocco Di Leo, MCs in Mechanical Engineering. PhD student in Mechanical Engineering at the University of Salerno (Italy). His research activity deals with the development and experimengtal validation of control oriented modelsfor internal combustion engines.Since 2014 he is involved in experimental activities on light-duty Diesel engines at the test bench of the University of Salerno.