Estimation of in-cylinder mass and AFR by cylinder pressure measurement in automotive Diesel engines

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Abstract: In the last decades the role of the engine control has became fundamental to improve fuel consumption and comply with the emissions standards. Particularly on automotive Diesel engines sophisticated control systems have been introduced, which are based on both large measurement data sets and complex controllers. Alternatives are needed to simplify and improve the Engine Management System (EMS). To this purpose the in-cylinder signal may be an effective measure to enhance EMS and its reliability, as well as to potentially reduce both costs and development time.

The paper deals with the development of two techniques to estimate the Air-Fuel Ratio (AFR) and the in-cylinder mass from the in-cylinder pressure signal. These methodologies are intended to be implemented in real-time with the aim of replacing or working jointly with the existing air mass flow and lambda sensors. The techniques were validated vs. experimental data measured at the engine test bench on a Common Rail light-duty Diesel engine. The results show a good accuracy in predicting Air-Fuel Ratio and in-cylinder mass in a wide engine operating range.

Keywords: Engine modelling and control; Modeling, supervision, control and diagnosis of automotive systems.

1. INTRODUCTION

Automotive engines and control systems are becoming more and more sophisticated due to increasingly restrictive environmental regulations. Estimation of engine states and outputs is requested in steady-state and transient operation to control the large number of actuators and many sensors are used for this purpose. Theoretically, most of the information provided by the sensors may be derived from the in–cylinder pressure. Its measurement might allow replacing part of the existing sensors, with a potential reduction of cost and system–complexity. Moreover, the pressure signal exhibits high dynamic features that are beneficial for a tighter control. However, suitable methodologies should be applied to deal with the critical issues related to in-cylinder pressure processing and detect information for both control and monitoring purposes. To this end, empirical, statistical or phenomenological approaches are required. In case of empirical and statistic techniques, the synthesis of the in-cylinder pressure is carried out by means of characteristic indexes, whose selection is essential to guarantee satisfactory accuracy in a wide engine operating range.

The use of cylinder pressure as a comprehensive measure for engine control and diagnosis has been investigated in the last four decades by several authors. It can be used for a wide range of applications, such as spark advance and misfire detection (Yoon, 2000; Leonhardt, 1999), cold start, injection pattern and combustion phasing control (Tunestal, 1999; Leonhardt, 1995; Yoon, 2007), estimation of inducted air mass (Mladek, 2000) and exhaust emissions (Beasley, 2006). For the sake of conciseness, the reader is addressed to Powell (1993) which gives an exhaustive survey on the application in SI engines for spark timing and AFR control, intake mass estimation and misfire detection. Despite its promising performance, the application of Pressure Based Control (PBC) was inhibited in the last two decades by the high cost of the pressure sensors. Nowadays, cheaper solutions are coming up and PBC may become an effective methodology for the next future, particularly for Diesel engine control, due to its higher complexity than SI engine.

In the paper two techniques are presented to estimate the Air-Fuel Ratio and the in-cylinder mass in Diesel engines, based on the in-cylinder pressure signal. The AFR estimation enhances the feedback control of injection pattern and air path, to guarantee the target engine performance and emissions, as well as to manage cold-start and transient operation. The proposed technique allows estimating the in-cylinder AFR based on the statistical moments of the pressure signal, without the typical

limitation of the AFR measurement, affected by UEGO sensor time response and gas transport delay (Arsie et al., 2010). Furthermore, the authors propose a methodology to estimate the inducted air-mass from the pressure gradient, with the aim of replacing or working jointly with the existing air mass flow sensors.

2. EXPERIMENTAL SET-UP

The engine investigated is a 1.3 liters, 4 cylinders, Common-Rail Diesel engine, equipped with VGT turbocharger and high pressure EGR. The techniques were validated against a set of experimental data measured at the engine test bench in steady-state conditions. The data set is composed of 34 operating conditions distributed in the engine operating range as reported in Tab. I. Apart from the sensor measurements available from the EMS (i.e. air mass flow, boost pressure, injection pattern, AFR, etc...), the in-cylinder pressure and the EGR ratio were also measured for each operating condition. Particularly, the CO_2 concentration in the intake and exhaust manifolds, measured by an infrared analyzer, was used to estimate the experimental EGR rate.

The experimental data were used partly for parameters identification and partly for model validation.

Table I – Limit values of the experimental data set.

		Lower limit	Upper limit
Engine Speed	[rpm]	1000	4500
Torque	[Nm]	10	200
EGR	[%]	0	33
Air-Fuel Ratio	[/]	18	70

3. AIR-FUEL RATIO ESTIMATION

The AFR signal is fundamental to perform the closed-loop control of fuel injection pattern and air path (i.e. VGT) and is currently detected by a UEGO sensor located in the exhaust manifold. The technique implemented for the current application is derived from a work originally proposed by Gilkey and Powell (1985) for a Spark Ignition engine and lately applied by the authors themselves (Arsie et al., 1998). It is based on the use of statistical moments to describe the shape of the in-cylinder pressure trace along the engine cycle and, to the authors knowledge, it has not been applied yet for Diesel engines. It relies on the concept that a variation of AFR results in different value and position of the pressure peak with a change of its distribution with respect to its centroid. These considerations suggest that the central moments are strongly correlated with the AFR and can be exploited for its estimation. The n-th central moment is defined as:

$$M_n = \int_{-\infty}^{+\infty}(\theta - \theta_c)^n p(\theta)d\theta \tag{1}$$

where θ_c is the expected value of θ, also known as the center of gravity of the one dimensional mass distribution $p(\theta)$:

$$\theta_c = \frac{M_1}{M_0} = \frac{\int_{-\infty}^{+\infty}\theta \cdot p(\theta)d\theta}{\int_{-\infty}^{+\infty}p(\theta)d\theta} \tag{2}$$

Through statistics considerations (Mood et al., 1974), the *2-nd* and *3-rd* order central moments are related with the spread and the symmetry of $p(\theta)$ with respect to θ_c. Moreover, a large *2-nd* central moment value denotes an high level of spread while a narrow distribution around the expected value exhibits a small value; the sign of the *3-rd* order central moment indicates in which semiplane $(-\infty, \theta_c)$ or $(\theta_c, +\infty)$ the data distribution is more populated.

The statistical moments are computed by focusing the cylinder pressure trace into the combustion interval, as suggested by Gassenfeit (1989) for a Spark Ignition engine. For a Diesel engine, such period is identified from the heat release rate (shown in figure 1) as the time interval between 2% and 98% of the fuel burned fraction. The figure 2 shows an example of the pressure trace considered and the calculated centroid.
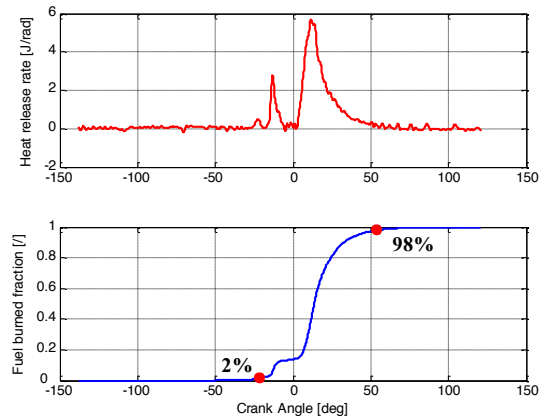

Figure 1 – Heat Release Rate (upper) and fuel burned fraction (lower). Engine speed = 2000 rpm, bmep = 13 bar.

As suggested by Gassenfeit & Powell (1989) and Patrick & Powell (1990), the central moments are divided by the area of the pressure cycle in motored condition (i.e. without combustion):

$$A_u = \int_{\theta_{ign}}^{\theta_{ign}+\Delta\theta_{comb}} p_{back}(\theta)d\theta \tag{3}$$

The pressure cycle in motored condition was calculated by the polytropic relationship:

$$p_{back}(\theta) = p(\theta_{IVC})\left(\frac{V(\theta_{IVC})}{V(\theta)}\right)^m \tag{4}$$

The polytropic exponent m was identified as a mean value on the available experimental pressure cycles and was set to 1.32.

After the standardization with respect to the area A_u, the influence of low pressure measurement uncertainty is reduced, thus allowing the application of the global technique even in case of pressure traces measured by low cost sensors.

$$M_2 = \frac{\int_{\theta_{ign}}^{\theta_{ign}+\Delta\theta_{comb}} (\theta - \theta_c)^2 \, p(\theta) d\theta}{A_u} \qquad (5)$$

$$M_3 = \frac{\int_{\theta_{ign}}^{\theta_{ign}+\Delta\theta_{comb}} (\theta - \theta_c)^3 \, p(\theta) d\theta}{A_u} \qquad (6)$$

Moreover, since the analysis is carried out on a Diesel engine, which can operate with very lean mixtures, the AFR was replaced with the equivalence ratio ϕ to narrow the values range.

The Figure 2 shows, as an example, the in-cylinder pressure trace at 2000 rpm and bmep = 13 bar. The combustion interval is evidenced in yellow and the red point is the centroid of the distribution.
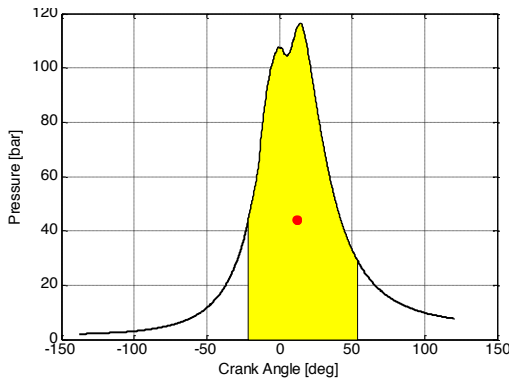

Figure 2 – In-cylinder Pressure Trace at 2000 rpm and bmep = 13 bar. The combustion interval is evidenced in yellow; the red point is the centroid of the distribution.

The Figures 3 and 4 show the trends of the second and third moments with respect to the equivalence ratio ϕ, on the whole set of experimental data available. The Figures evidence that for very lean mixtures the second and, especially, the third moment have an asymptotic trend towards zero. Such result is explained by the tendency towards a simmetrical pressure distribution in case of lean mixtures. It is then difficult to obtain a good prediction of ϕ in this region without considering additional variables.

A stepwise algorithm was then applied, considering the engine variables mostly affecting ϕ, among those available from EMS and in-cylinder pressure measurement, such as engine speed, intake manifold pressure and statistical moments. Finally, the following relationship was identified, expressing the equivalence ratio as function of 2nd and 3rd normalized moments (M_n), including the dependence of engine speed (N):

$$\phi = a_0 + a_1 M_2 + a_2 \frac{1}{M_2} + a_3 \frac{M_3}{M_2} + a_4 N^2 \qquad (7)$$

The model parameters a_n were identified by a Least Square Technique comparing estimated (i.e. eq. 7) and measured ϕ values over a set of data (i.e. identification data set) composed of 50 % of the whole experimental data set available.
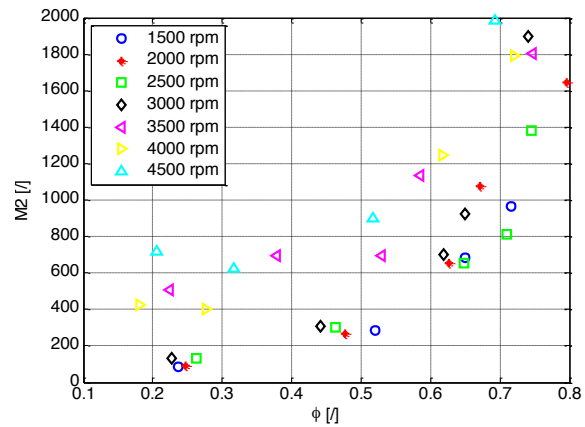

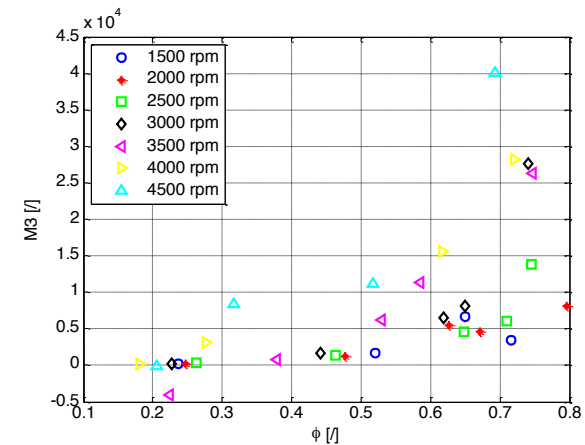Figure 3 – Effect of the equivalence ratio on the second statistical moment, at different engine speed.

Figure 4 – Effect of the equivalence ratio on the third statistical moments, at different engine speed.

The validation results are reported in Figure 5 and Figure 6. Particularly, the Figure 5 shows the comparison between predicted and measured equivalence ratio ϕ while the Figure 6 shows the absolute error distribution between estimated and measured ϕ. Both figures show a satisfactory accuracy of the technique in predicting the equivalence ratio, as confirmed by a correlation index R^2 equal to 0.996 and mean absolute and relative errors equal to 0.04 and 9.78 %, respectively.
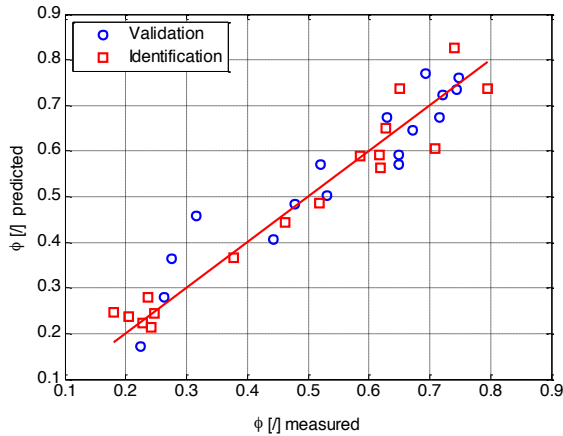
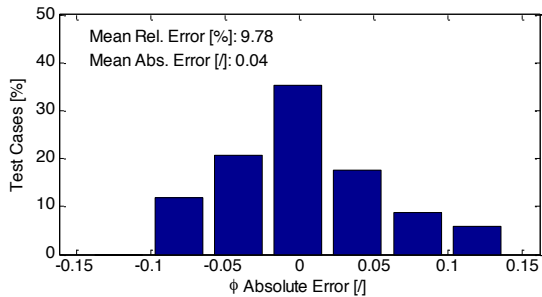Figure 5 – Predicted vs. measured ϕ for the identification and validation data sets. $R^2 = 0.996$.

Figure 6 – Absolute Error distribution between estimated and measured ϕ.

4. IN-CYLINDER MASS ESTIMATION

The estimation of the in-cylinder trapped mass is fundamental to actuate a suitable control of engine combustion and after-treatment devices. On current production engines it is usually performed by the air mass flow sensor and the EGR estimation. Many works deal with this issue (e.g., Colin et al. 2007, Desantes et al. 2010, Jeremy 2005) and different pressure-based techniques have been proposed. In the current paper the delta-P method is applied, starting from the work of Desantes et al. (2010). The innovative contribution herein lies in the reduced number of engine variables considered.

The method is based on the knowledge of in-cylinder pressure in two points of the compression phase, denoted by a and b, respectively. The in-cylinder trapped mass is then estimated, based on the pressure rise between these two points. Assuming an ideal behaviour of the mixture, the delta-P method exploits the ideal gas law and the polytropic compression relationship, expressed by the following equations:

$$p_a V_a = m_{ivc} R T_a \tag{8a}$$

$$p_b V_b = m_{ivc} R T_b \tag{8b}$$

$$p_a V_a^{\ k} = p_b V_b^{\ k} \tag{9a}$$

$$T_a V_a^{\ k-1} = T_b V_b^{\ k-1} \tag{9b}$$

Matching the equations (8) and (9), the in-cylinder trapped mass is expressed as function of the measured delta-P:

$$m_{ivc} = \frac{\Delta p V_a}{R T_a} \left\{ \left(\frac{V_a}{V_b} \right)^k - 1 \right\}^{-1} \tag{10}$$

Once the polytropic coefficient k is known, the only variable to be defined is T_a. This latter depends on the heat transfer and the pressure rise, which are obviously related to the specific operating condition.

A black-box model expressing the in-cylinder temperature T_a as function of the available engine variables was then developed. Particularly, a stepwise procedure was applied to select the most effective variables, leading to the following model equation, dependent on the engine speed (N) and the injected fuel mass (m_f):

$$T_a = c_0 + c_1 N^2 + c_2 m_f^{\ 2} + c_3 \frac{1}{N^3} + c_4 m_f^{\ 3} N \tag{11}$$

It's worth noting that the number of measured variables in eq. (11) is significantly lower than those considered in the application presented by Desantes (2010). Furthermore, all the variables in eq. (11) are easily available from the production EMS, thus avoiding the use of additional sensors and enhancing the feasibility of the on-board implementation.

Since the experimental in-cylinder temperature was not available, the reference temperature T_a, considered for model identification and validation, was calculated by inverting eq. 10. The reference experimental in-cylinder trapped mass m_{ivc}, was evaluated by processing the measured air mass flow and the EGR rate derived by CO_2 measurement in the intake and exhaust manifolds. The effect of residual gas fraction and backflow were not considered, because of their negligible contribution.

A detailed analysis was finally carried out to evaluate the impact of the Δp interval on model accuracy. Table II shows the mean relative errors between experimental and predicted air-trapped mass, for a set of Δp intervals. The reference operating conditions are indicated in Tab. I.

As evidenced in Tab. II, moving the point b toward the TDC gives better results. Nevertheless, a further delay of the point b would be not convenient due to possible superposition with the fuel injection. Similarly, setting the point a close to the IVC may compromise the accuracy, due to the influence of the wave effects related to the intake process. Finally, a Δp between -70° and -50° ATDC was selected, considering that the maximum pilot injection advance for the experimental data considered was set to 45° BTDC.

Tab. II – Mean relative error for different Δp intervals.

Points	b			
	Crank Angle [deg]	-110°	-90°	-70°	-50°
a	IVC	-2.51	-0.86	-0.30	-0.22
	-110°		0.059	-0.076	-0.0061
	-90°			-0.36	-0.083
	-70°				-0.0071

The Figure 7 shows the comparison between predicted and experimental in-cylinder trapped mass.

The results exhibit very good model accuracy in estimating the in-cylinder trapped mass, particularly in the operating conditions with high EGR (i.e. low load operation), with an overall correlation index R^2 equal to 0.997. The Figure 8 shows the distribution of the absolute error between predicted and experimental trapped mass, which exhibits mean absolute and relative errors equal to 6.37 mg and 1.35 %, respectively.
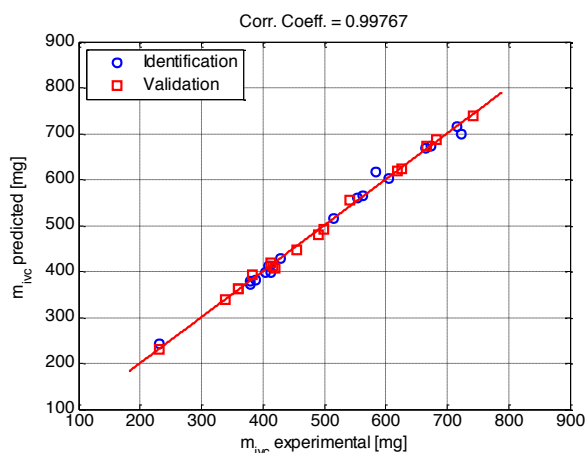

Figure 7 – Predicted vs. experimental in-cylinder mass for the identification and validation data sets. $R^2 = 0.997$.
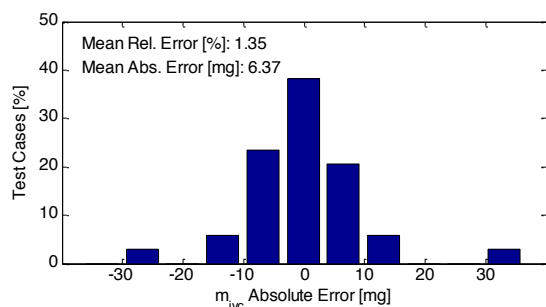

Figure 8 – Absolute Error distribution between predicted and experimental in-cylinder trapped mass.

5. CONCLUSIONS

Two techniques have been presented to estimate AFR and in-cylinder trapped mass, based on the in-cylinder pressure signal. The methodologies were validated against a set of experimental data measured at the test bench on a light-duty Diesel engine equipped with VGT and EGR. The validation results show a good accuracy in predicting both AFR and in-cylinder mass, with mean relative errors in the whole set of data investigated equal to 9.78 % and 1.35 %, respectively.

The accuracy achieved and the low computation demand enhance the on-board application of the two techniques with the aim of replacing the existing air mass flow and lambda sensors to reduce costs or jointly operating with them to improve EMS reliability.

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NOMENCLATURE

Latin symbols

AFR	[/]	Air-Fuel Ratio
$ATDC$	[deg]	degree After Top Dead Center
A_u	[bar]	pressure cycle area in motored conditions
a_n	[/]	n-th regression constant
c_i	[/]	i-th regression constant
IVC	[deg]	Intake valve closing
k	[/]	polytropic relation exponent
M_n	[/]	n-th order central moment of pressure data distribution
m_f	[mg]	fuel mass
m_{ivc}	[kg]	air mass at IVC
N	[rpm]	engine speed
p	[bar]	in-cylinder pressure
p_{back}	[bar]	in-cylinder pressure in motored conditions
R	[J/kg/K]	gas constant
R^2	[/]	correlation index
T	[K]	in-cylinder temperature
V	[m^3]	actual displaced volume

Greek symbols

ϕ	[/]	equivalent ratio
θ	[deg]	actual crank angle
θ_c	[deg]	centroid crank angle
θ_{ign}	[deg]	ignition crank angle
$\Delta\theta_{comb}$	[deg]	combustion duration

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