

A Control-Oriented Knock Intensity Estimator

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ABSTRACT

The performance optimization of modern Spark Ignition engines is limited by knock occurrence: heavily downsized engines often are forced to work in the Knock-Limited Spark Advance (KLSA) range. Knock control systems monitor the combustion process, allowing to achieve a proper compromise between performance and reliability. Combustion monitoring is usually carried out by means of accelerometers or ion sensing systems, but recently the use of cylinder pressure sensors is also becoming frequent in motorsport applications. On the other hand, cylinder pressure signals are often available in the calibration stage, where SA feedback-control based on the pressure signal can be used to avoid damages to the engine during automatic calibration.

A predictive real-time combustion model could help optimizing engine performance, without exceeding the allowed knock severity. Several knock models are available in the literature: most of those proposed for real-time applications are single zone or two-zone models, grounded on more complex CFD simulations. However, since the knock phenomenon is influenced by several factors, the real-time determination of KLSA requires the model to be adapted to the engine actual behavior. The approach proposed in the present paper, is based on the constant adaptation of a two-zone model to measured cylinder pressure data: typical results of the indicating analysis, available cycle-by-cycle and cylinder-by-cylinder, are used as inputs for the model, with the aim of predicting KLSA for the current running condition, without exceeding the maximum allowed knock intensity.

The approach has been applied to indicating data referring to non-knocking, light and heavy knocking conditions, showing a good prediction capability.

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INTRODUCTION

Pressure-based combustion controls are becoming common in automotive engines management systems: many work in the literature can be found regarding the use of cylinder pressure sensors for the control of combustion phase, for standard production diesel engines ([1, 2, 3, 4, 5, 6]) and prototype engines with innovative combustion approaches, such as Homogeneous Charge Compression Ignition (HCCI) [7, 8, 9], Reactivity Controlled Compression Ignition (RCCI) [10], Low Temperature Combustion (LTC) [11-12], Gasoline Compression Ignition (GCI) [13-14]. Other works focus on different benefits that can be obtained from the use of the pressure signal, such as air charge and residual gas estimation [15-16], Air-Fuel Ratio (AFR) estimation [17-18], pollutant emissions estimation and control [19]. The feedback control of pressure sensors is certainly used in many motorsport applications, such as Formula 1, as it can be inferred by FIA delegate reports [20]. The management of control parameters based on the cylinder pressure information is also common during the engine development stage, especially in the calibration phase ([21-22]): one of the tasks performed during calibration thanks to cylinder pressure technology is knock diagnosis, that is typically carried out analyzing the high-frequency content of the signal ([23]). The assessment of knock intensity is usually obtained applying statistical analyses to large

data samples, containing knock indexes referring to several hundredths of engine cycles. This means that not only the assessment is not predictive, but it requires many engine cycles sampled in knocking conditions, for the determination of knock severity. Thus, the evaluation of Knock Limited Spark Advance (KLSA) requires exceeding the acceptable statistical knock intensity threshold, which may lead to engine damages. A real-time combustion model using as inputs the indicating data, able to predict the knock limit before dangerous knock intensity conditions are reached, would be very useful during engine development stages. Furthermore, for those applications where the cylinder pressure signal is available on-board, the model would improve engine performance: KLSA may change, depending on the piston thermal history ([24]), and a real-time model using indicating data would allow tuning the Spark Advance setting according to the actual running condition. For example, KLSA value estimated by the model at the beginning of a straight in a track during a race would be higher, compared to that evaluated at the end of the straight.

Many real-time compatible knock models can be found in the literature: some of them are meant for pre-calibration [25], other for Software or Hardware in the Loop simulations [26]. The presented approach is focused on the real-time execution of the model, with particular attention to its adaptation to actual cylinder pressure data.

Although the methodology is grounded on the availability of cylinder pressure signals, it has been developed based on cycle-based data (e.g., MFB10, MFB50, MAPO, CHR_{net}) only. On one hand, this approach can be applied when the engine control system has not direct access to cylinder pressure signals, but receives indicating data cycle-by-cycle from a Combustion Analysis System (CAS): this is what usually happens during engine calibration. On the other hand, it could enable the use of the same methodology when indicating data are estimated, based on different signals [27, 28, 29]. Necessary information on the pressure trace evolution will thus be inferred, based on synthetic combustion tracers, such as MFB10, MFB50 and CHR_{net} .

COMBUSTION MODEL

A real-time knock control strategy aimed at preventing engine damages should ground on the following modelling features:

1. the use of easily accessible combustion information, i.e., synthetic cycle-based indicating data;
2. low computational power requirements. The model should be in the form of analytical functions, with explicit integration of derivative equations;
3. predictive of severe knocking events, to prevent the risk of damage;
4. adaptive to the actual operating condition of the engine with a few tuning parameters;
5. inclusive of stochastic model variables, to face with the cycle by cycle variability of engine combustions.

Most of the knock models proposed in the literature [30] are based on the estimation of autoignition time by means of chemical (detailed or reduced [31]) kinetic sub-models, or on empirical correlations (Livengood and Wu [32]).

Millo et Al. [33] proposed a Kinetics Fit model of knock, in which the phenomenological equations of the induction time are tuned against detailed chemistry simulations. In the present work, a two steps chemistry model is presented, following the main structure proposed by Millo et Al. The first step of the model makes an estimation of the autoignition time of the mixture, the second step reproduces the effects of abnormal combustions on the pressure signal.

The induction time of knock is based on the Arrhenius-type equation of three different regions of temperatures:

$$\frac{1}{\tau} = \frac{1}{\tau_1 + \tau_2} + \frac{1}{\tau_3} \quad (1)$$

Where τ_1 and τ_2 represent the induction times for low and intermediate level of temperatures, while τ_3 relates to the higher one. In the actual implementation, each induction time has the following form:

$$\tau_i = A_i p^{-n_i} \exp\left(\frac{B_i}{T_u}\right) \varphi^{x_i} \quad (2)$$

Where p , T_u and ϕ are pressure, temperature and equivalence ratio of the unburned mixture, while A_i , n_i , B_i and x_i are the constants referred to each level of temperature. Following the model structure of Millo et Al [33], these constants come from a fitting procedure on the results of a kinetic tabulated map obtained by means of Cantera code [34, 35].

The first knock tracer index kn_{trac} is calculated by the following integral over the compression and expansion strokes:

$$kn_{trac} = \int_{IVC}^{EVO} \frac{dt}{\tau} \quad (3)$$

kn_{trac} is based on the thermodynamic variables of unburned fresh mixture on a crank angle basis, whose evaluation was accomplished by means of few simplified hypotheses in the equation of conservation of energy.

The evolution of the overall combustion progress variable is synthesized by a linear fitting, passing through MFB10 and MFB50. This choice was driven by the needs of lowering the computational cost of interpolating a Wiebe function: Figure 1 shows that the accuracy of the linear model is good within MFB10 and MFB85. On one hand, the contribution to the knock tracer integral with mass of fuel burned lower than 10% is negligible, on the other hand, the most likely values of X_b at knock onset are lower than 90%.

The overall evolution of pressure on a crank angle basis comes from the explicit integration of the first law of thermodynamics applied to the whole mass in the chamber:

$$\frac{dp}{d\theta} = \frac{1}{V} \left((k-1) \frac{dX_b}{d\theta} CHR_{net} - k p \frac{dV}{d\theta} \right) \quad (4)$$

where p is the mean pressure in the chamber, V is the cylinder volume, CHR_{net} is the net cumulative heat release of the cycle.

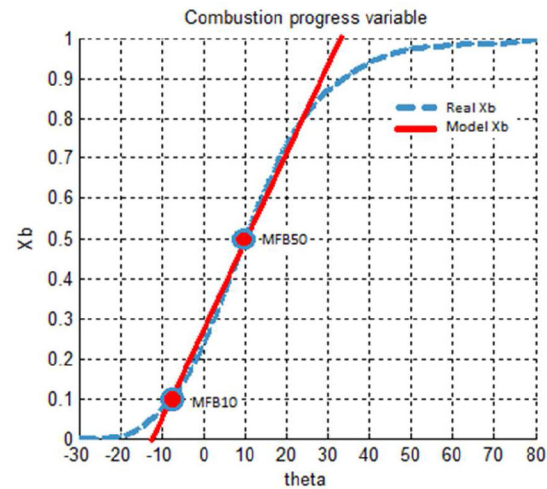


Figure 1. Combustion progress variable X_b

Equation (4) is necessary if the control system implementing the KLSA estimation does not have access to the pressure samples, but only to cycle-based indicating parameters (namely, MFB10, MFB50, CHR_{net}): it represents the inversion of the same procedure used by the CAS system for the calculation of combustion variables, thus the estimation of pressure should be accurate, using the same k value. The pressure of the unburned mixture is supposed to be equal to the calculated mean value in the cylinder.

The estimation of the unburned temperature T_u comes from the integration of the energy balance of the unburned zone ([36-37]):

$$\frac{dT_u}{d\theta} = \frac{1}{c_p m (1-X_b)} \left[\frac{1}{\omega} A_u h_u (T_u - T_w) + V_u \frac{dp}{d\theta} \right] \quad (5)$$

Where c_p is the specific heat capacity, m the total mass in the cylinder, h_u [33] is the heat transfer coefficient in the unburned zone, A_u and V_u respectively the area and volume, ω engine speed. The integration of equation 5 is explicit and an estimation of the temperature T_u at IVC (T_{IVC}) is necessary: the initial T_u can be evaluated on a first attempt by means of the ideal gas law (based on the knowledge of cylinder pressure), or by results from 1D CFD simulations. Knock estimation is highly dependent on the identification of T_{IVC} , for this reason this starting temperature for equation 5 is subject to a tuning procedure for each cylinder and for every considered operating point, as it will be shown later in this work. kn_{trac} can be calculated for each engine cycle, leading to the prediction of knock when its value exceeds 1.0.

The second step of the model is the identification of the effects on pressure signal when abnormal combustions occur. With the hypothesis [31] that all the unburned fuel at knock onset (i.e. kn_{trac} reaches 1.0) suddenly burns, the estimation of pressure step caused by knock is:

$$\Delta p_{knock} = \frac{(k-1)}{V} ((1 - X_b) CHR_{net}) \quad (6)$$

The knock index used for the identification of damage risk is finally defined as:

$$kn_{index} = k_1 \frac{rpm}{1000} kn_{trac} + k_2 \max(0, kn_{trac} - 1) \Delta p_{knock} \quad (7)$$

Where k_1 and k_2 are model tuning constants. This definition of kn_{index} allows the model being directly comparable to the MAPO (Maximum Amplitude of Pressure Oscillations) [38], one of the most used indicating parameters for knock detection, defined as

$$MAPO = \max(|p_{fit}|_{\theta_s}^{\theta_e}) \quad (8)$$

The first term of equation (7), correlates the rate of combustion (represented by kn_{trac}) to the pressure oscillation in case of normal combustions. This correlation (intrinsically included in the widely used MAPO thresholds definition of rpm/1000) accounts for the Arrhenius-like definition of kn_{trac} and it is in line with the model suggested by Millo et Al. [33]. The second term of equation (7) allows adding the contribution of the pressure wave caused by knocking combustions.

Knock is a stochastic phenomenon and a real-time model should be able to represent both the variability of combustion and knocking events. In a previous work [38] the authors made an extensive use of CFD 3D analysis to reconstruct the correlations between variability of combustion and knock. Cycle by cycle instability is intrinsically included in the variability of the combustion angles (MFB10 and MFB50) used for the calculation of knock index. However, knock phenomenon is not solely identifiable by mean combustion angles: D'Adamo et Al [39] showed how a spatial distribution of temperature and mixture fraction clearly correlates with variability of knock events.

For this purpose, the unburned temperature T_u used in the integration of induction time is randomly chosen according to a normal distribution with standard deviation $\sigma(T_u)$ and a mean value predicted by means of equation (5). This deviation of temperature T_u from the mean value physically represents the probability of a spatial location to be in the last unburned zone of combustion. In the actual engine, the estimation of spatial distribution of T_u is $\sigma(T_u) = 7K$.

Figure 2 shows the evolution of the predicted and experimental MAPO indexes in two different engine operating conditions. Overall, the sensitivity of the model to combustion variability is good: the variability of temperature in the unburned zone allows better identifying the abrupt increase of MAPO with the fastest combustions. Once identified for significant running conditions, with different engine speed and knock intensities, the model constants k_1 and k_2 are kept constant for all the evaluations presented in this work.

EXPERIMENTAL SETUP

The engine under analysis is a Ducati-high performance unit, whose characteristics and running conditions are reported in Tab. 1. In order to increase the volumetric efficiency at high engine speed, a wide intake valve opening duration has been set, which makes the actual compression ratio lower than the geometric value. However, due to the ram and pressure waves tuning effects knocking combustions can happen even at high engine speed.

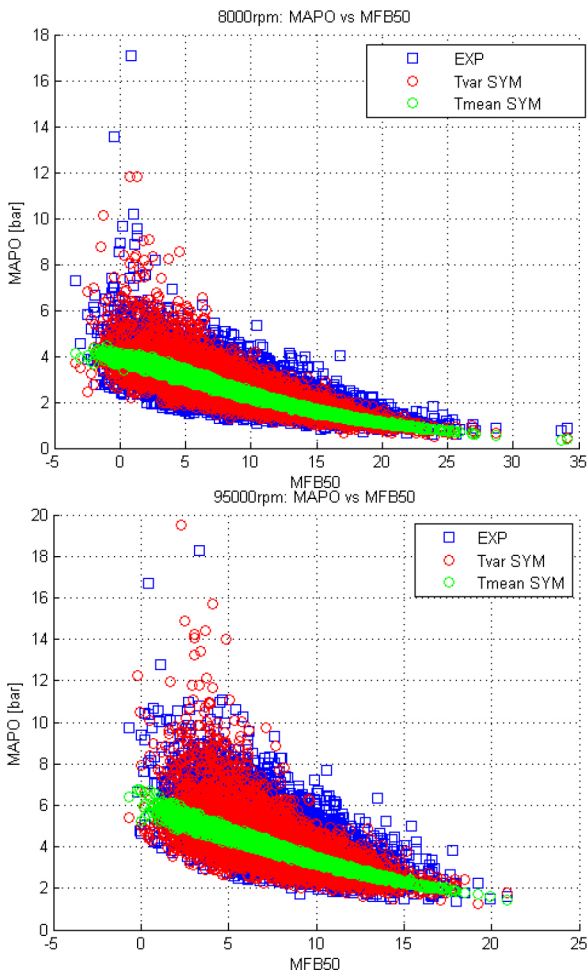


Figure 2. scatters of experimental and simulated MAPO versus MFB50

Table 1. Engine characteristics

Displaced volume	1198 cc
Bore x stroke	106x67.9 mm
Connecting Rod	122.5 mm
Compression ratio	12.8:1
Cylinders Configuration	V2, 90°
Intake Valve Opening	18°BTDC→58°ABDC
Exhaust Valve Opening	58°BBDC→23°ATDC
TEST CONDITIONS	
Engine Speed	5000, 7000, 8000, 9500 rpm
Engine Load	WOT
Lambda	0,87

The engine was tested on the test bench using Kistler 6052C32U20 cylinder pressure transducers and Alma Automotive Champion charge amplifier. An OBI-M2 Combustion Analysis System has been used to sample and analyse cylinder pressure, intake pressure, and actuations (coil charging and injection) signals. Pressure traces referring to more than 1000 engine cycles have been recorded for each engine operating point, for several different Spark Advance values. The signals are sampled @ 400kHz after a low-pass anti-aliasing filter (Butterworth, 3rd order, 100 kHz). The evaluation of Indicated Mean Effective Pressure (IMEP), Rate of Heat Release

(ROHR), Cumulative Heat Release (CHR) and therefore angle of Mass Fraction Burnt (MFB) has been carried out after a low-pass zero-delay 2nd order Butterworth digital filter, with cut-off frequency set to 2.5 kHz. The evaluation of MAPO knock index has been obtained using a high-pass zero-delay 2nd order Butterworth digital filter, with cut-off frequency set to 5 kHz.

Although it would be possible to re-process sampled data off-line, the model and its application framework have been developed using the indicating parameters evaluated in real-time by the combustion analysis system. The CAS is able to send these data on the CAN bus, using a dedicated port, publishing them cylinder by cylinder, right at the end of each exhaust stroke, which allows closing the loop on the actuation (SA) within the next engine cycle. By feeding the knock simulation with the parameters evaluated in real-time it is possible to assess the actual performance attainable running the model in real-time using the feedback of the CAS.

REAL-TIME MODEL ADAPTATION TO INDICATING DATA

The Combustion Analysis System outputs several parameters for each cylinder and every engine cycle. These parameters may be used to feed the model, at the same time checking its ability to predict knock intensity. The model is then re-calibrated if predicted knock intensity is far from the measured value: the calibration is carried out only if measured or predicted knock intensity falls over a given threshold.

Since the simulated phenomenon is stochastic, a probabilistic analysis is applied to raw cycle-based knock intensity indexes (MAPO), so that the comparison of experimental and simulated series is carried out on a statistical basis. A common approach to the assessment of knock severity ([40]) is to use the MAPO intensity corresponding to a given probability: in this case the 99th percentile has been selected.

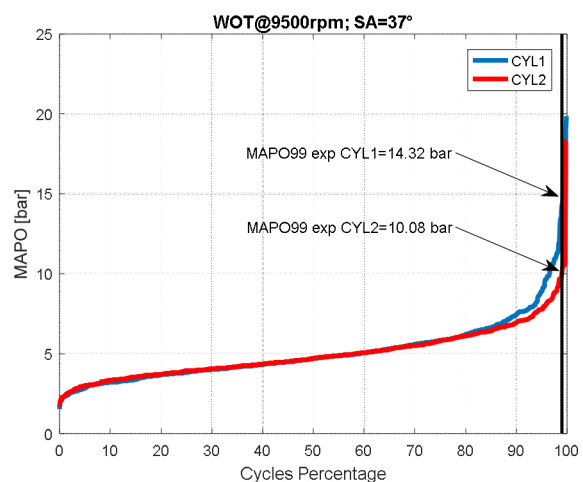


Figure 3. statistical knock indexes (MAPO99): experimental results

Figure 3 shows how the statistical knock intensity index (MAPO₉₉) is evaluated, sorting the elements (MAPO values pertaining to a given running condition and SA setting) in the buffer, and then selecting the value corresponding to the 99% position.