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Energy Procedia 45 (2014) 967 – 976

Energy Procedia

68th Conference of the Italian Thermal Machines Engineering Association, ATI2013

Transient spark advance calibration approach

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Abstract

Combustion control is assuming a crucial role in reducing engine tailpipe emissions while maximizing performance. The effort in the calibration of control parameters affecting the combustion development can be very demanding. One of the most effective factors influencing performance and efficiency is the combustion phasing: in Spark Ignition (SI) engines it is affected by factors such as Spark Advance (SA), Air-Fuel Ratio (AFR), Exhaust Gas Recirculation (EGR), Variable Valve Timing (VVT).
SA optimal values are usually determined by means of calibration procedures carried out in steady state conditions on the test bench by changing SA values while monitoring performance indicators, such as Brake and Indicated Mean Effective Pressure (BMEP, IMEP), Brake Specific Fuel Consumption (BSFC) and pollutant emissions. The effect of SA on combustion is stochastic, due to the cycle-to-cycle variation: the analysis of mean values requires many engine cycles to be significant of the performance obtained with the given control setting. Moreover, often the effect of SA on engine performance must be investigated for different settings of other control parameters (EGR, VVT, AFR). The calibration process is time consuming involving exhaustive tests followed by off-line data analysis.
This paper presents the application of a dynamic calibration methodology, with the objective of reducing the calibration duration. The proposed approach is based on transient tests, coupled with a statistical investigation, allowing reliable performance analysis even with a low number of engine cycles. The methodology has been developed and tested off-line, then it has been implemented in Real-Time. The combustion analysis system has been integrated with the ECU management software and the test bench controller, in order to perform a fully automatic calibration.

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Keywords: Calibration; Spark Advance; Knock; Combustion Analysis; cylinder pressure.

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1. Introduction

Spark Ignition engines performance are influenced by combustion phasing and duration: these parameters are affected by the Spark Advance setting. Electronic Control Units usually mange SA in open loop, selecting from

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doi:10.1016/j.egypro.2014.01.102

lookup tables or grey box models the values corresponding to the engine state [1]. SA is also used for torque management purposes, thus not only optimal SA settings but also information on the engine response to SA variations may be useful. A calibration procedure is therefore required, to determine SA values that will be used by the ECU during engine operation. The process is usually carried out on the test bench, keeping the engine in steady conditions for many engine cycles (sometimes thousands), to filter out the effect of stochastic phenomena (cycle-to-cycle variation, knock). Data are usually collected following a speed-load matrix: for each breakpoint defining the engine operating condition many tests are carried out, with different SA values. SA sweeps must be performed for different engine speed, load, and, sometimes, AFR, VVT, oil/water temperature, gasoline temperature, etc. The definition of SA maps is time-consuming, and, especially in racing applications, very expensive, due to the short engine life and the risk of exploring dangerous (knocking) running conditions during the sweep.

Combustion information gathered by means of in-cylinder pressure sensors can be used to highlight the effect of control variables on the output, but the same approach can be applied using other signals [2-9].

The typical calibration approach is ‘static’: the actuations to optimize vary according to a matrix that can be defined by means of Design Of Experiment (DOE) techniques ([10, 11]). Many examples can be found in the literature, based on the evolution of the described concepts: Halliday et al. (in [12]) and Rose et al. (in [13]) show how two-stage techniques can be successfully applied in engine mapping operations. This approach catches the different nature of the experiment factors (throttle opening, engine speed, SA) on the optimization output (engine torque), but it is still based on steady state tests. Furthermore, the methodology is entirely based on a black-box model, which means that many phenomena are condensed in few simple mathematical relationships: this could lead to a lack of robustness. A possible solution is to use more complex mathematical regressions, as shown in [14], where radial basis functions are proposed instead of polynomial models. Suzuki et al. in [15] propose a different way, using model-based methodologies for the calibration process, employing both cycle simulation and regression analysis. The model-based approach improves the robustness, but still the methodology requires steady state tests.

Other authors approach the problem of SA calibration (for Maximum Brake Torque, MBT) from a different point of view, defining a combustion invariant able to represent the optimal combustion phasing condition. Eriksson in [16] shows that an appropriate parameter is the MFB45, while Haskara et al. in [17] leans toward the maximum mass fraction acceleration. These methodologies tend to fail in particular running conditions, such as low loads, high Exhaust Gas Recirculation (EGR), etc. Besides, it has been shown [18, 19] that it is not necessary to set a well-defined value for the optimal combustion phasing throughout the entire engine operating range, simply because the optimal condition can be easily determined during the engine operation.

In [20] Patterson proposes a methodology aimed at setting the optimal SA during engine speed sweeps (with constant throttle position). A target combustion phase is assigned, and SA is changed sweep after sweep, driving the cylinders combustion phasing towards the target. The drawback of this technique consists in the definition of the target combustion phase, its value being influenced by operating conditions.

This paper propose an alternative 'dynamic' approach for the determination of the optimal combustion phase, maintaining the engine speed sweep test concept. A statistical analysis of combustion data is carried out in order to decrease the number of engine cycles required for the analysis.

Nomenclature

A, B, C, D	Parameters for $MAPO_{98}$ exponential interpolation
L	Lognormal Cumulative Probability Density Function
l	lognormal probability density function
$MAPO_{98}$	Value of MAPO corresponding to the 98^{th} percentile of the MAPO distribution
MFBxx	Angular Position corresponding to the xx% of fuel Mass Fraction Burned
N	Number of engine cycles used for statistical evaluations
P	Probability
p	Cylinder Pressure
α, β, γ	Quadratic (linear, constant) coefficient for the parabola fitting IMEP(MFB50)
μ_{MFB50}, σ_{MFB50}	MFB50 distribution mean value and standard deviation (over N cycles)
θ_{start}, θ_{end}	Knock detection window start angle/end angle

2. Experimental Setup

In order to define the calibration strategy tests have been carried out on the test bench on a Suzuki 4-cylinder 0.6 liters motorcycle unit, modified in order to accomplish the Formula SAE regulations.

The in-cylinder pressure signals have been sampled @100kHz and low-pass filtered by means of an anti-aliasing analog filter set @ 20 kHz: the filter delay has been compensated in order to avoid referencing errors. A 3 kHz zero-delay low-pass 4th order Butterworth digital filter has been used for IMEP and net Cumulative Heat Release (CHR) calculations, in order to eliminate the combustion chamber resonance effect.

The transient calibration methodology has been tested in real time on the same engine. The same system used for the acquisitions performs the breakpoint-related combustion analysis, and manages the communication with the ECU and the test bench controller.

In-cylinder pressure signals are sampled, filtered, placed on the angular domain and used for the cycle-by-cycle indicating analysis, thanks to the FPGA hardware [21]. The complete calibration application runs partly on FPGA-based hardware (NI PXI7854), partly on a real-time controller (NI PXI8110RT) and partly on the host computer.

3. Transient Spark Advance Calibration Methodology

The calibration process takes place with engine speed sweeps tests carried out at constant engine load. Sweep after sweep the values of SA stored in the ECU memory are automatically updated, finally reaching the optimal setting. The automation algorithm is based on the following steps

- definition of optimization targets
- definition of optimization constraints
- first attempt SA lookup table
- execution of speed sweep test
- combustion data analysis
- definition of new SA lookup table

The steps 4→6 are executed until stable values are reached for the estimated optimal SA values of each breakpoint (and each cylinder).

The optimization targets may vary depending on the application: engine torque maximization, specific fuel consumption and pollutant emissions (especially NOx) minimization are commonly used to drive the optimization. The present calibration application is focused on performance, thus the methodology aim is to maximize the IMEP of each cylinder. Another consideration has to be taken into account for the definition of the calibration strategy: the ECU could use suboptimal values during the engine use on road. The engine torque manager could require a torque reduction with respect to the maximum achievable in the given running conditions, due to the effect of strategies such as traction and vehicle dynamics control, or driveability. For this reason, at the end of the calibration process the entire trend of IMEP with respect to SA, should be available, and not only the MBT value. From this point of view, the best description of the engine behavior would be given by several equidistant SA tests, centered on the MBT value.

In the present application constraints are related to knock and misfire events. Depending on the running condition, exploring the SA range could lead to irregular combustions, that may cause damages to the engine or other components. Engine knock and misfire events are monitored and minimum/maximum allowable SA values are defined, based on combustion parameters. In order to avoid damaging the engine under test due to knocking SA values, a model is used to estimate knock intensity as a function of SA.

Since the MBT value is not known at the beginning of the calibration process, the first sweep is executed using a first attempt SA lookup table: cautious SA values must be chosen, in order to avoid engine knock and excessively high exhaust temperature. After the first speed sweep Spark Advance optimal values can be estimated, thus SA settings for the subsequent sweeps can be defined with respect to the MBT position.

All the evaluations concerning the combustion process are carried out considering the speed sweep as a sequence of steady state tests. Each speed breakpoint in the SA lookup table is then considered as the barycenter of an interval of engine cycles sampled during the transient test.

3.1. Optimal SA estimation

In a first stage, the optimal combustion phase determination is carried out exploiting the cycle-to-cycle variation, as shown in [18, 19]. SA effect on combustion is not deterministic: maintaining a given SA value, the MFB50 will show a given statistical distribution. This effect is mainly due to the variation of the ignition phase [22, 23], and propagates to the combustion phasing. The IMEP changes accordingly, forming a typical bell-shaped distribution in the plane IMEP-MFB50: the optimal MFB50 value corresponds to the vertex of the distribution, as it can be seen in Figure 1 (a). The MBT SA maintains the scatter near the top of the curve: this observation can be used to estimate the optimal SA right after the first sweep. The engine cycles distribution in the plane IMEP-MFB50 can be interpolated and the best combustion phase can thus be estimated. The difference between the actual and the optimal combustion phase will be a measure of the distance between the actual and optimal SA.

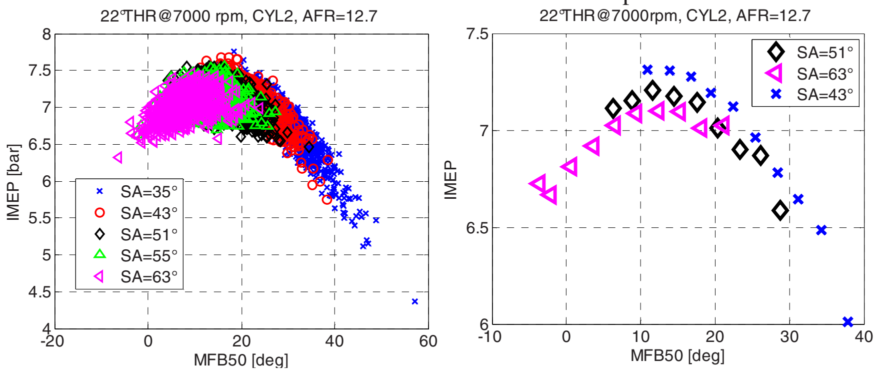

Figure 1(a): relationship between IMEP and MFB50 distributions; Figure 1(b): IMEP values vs. MFB50 class

On the other hand, figure 1 (a) shows that the clouds referring to different SA are partially superimposed: if two cycles obtained with different SA have the same MFB50, probably they will have different combustion duration. The same MFB50 could be the result of a slow-combustion high-SA cycle, or a fast-combustion low-SA cycle. Moreover, the indicated work is remarkably influenced by heat losses: this phenomenon is not entirely represented by MFB50, as great part of the heat is transferred to the cylinder walls in the later portion of the combustion [24], when the gas temperature is higher. Finally, MFB50 does not take into account directly for combustion inefficiencies and crevices filling-emptying effects, that may vary depending on SA.

These slight inaccuracies could result in setting a sub-optimal SA value. Figure 1 (b) shows how the distribution can change with SA variations: the same data shown in Figure 1 (a) are represented, grouped in MFB50 classes. It can be seen that the same MFB50 obtained with a different SA will lead to slightly different IMEP levels.

A calibration process targeted at the MFB50 corresponding to a symmetric scatter, could lead to a sub-optimal SA setting: this is a consequence of the under-parametrization of the combustion model considering IMEP as a function of a single parameter (MFB50).

Other phenomena could make the described approach inaccurate: in some cases, the optimal combustion phase simply cannot be reached. This happens when the operating conditions force to use very advanced ignitions, especially at high speed-low load, when the combustion speed can be very low (high amount of internal egr). It could happen that as SA is increased, the decreasing in MFB50 is small, while its standard deviation starts increasing rapidly.

This behavior is clearly represented in Figure 2 (a), that shows the results of a SA sweep carried out at high speed and low load. It can be noticed that for high SA values, SA increases have little effect on the combustion phase (MFB50) average value. At the same time, it is evident that MFB50 standard deviation rises sharply if the combustion is further advanced. The global effect is to lower the average IMEP as SA reaches high values, even if the best placement of the distribution scatter in the plane IMEP-MFB50 has not been reached. The best combustion phase in this case cannot be achieved.

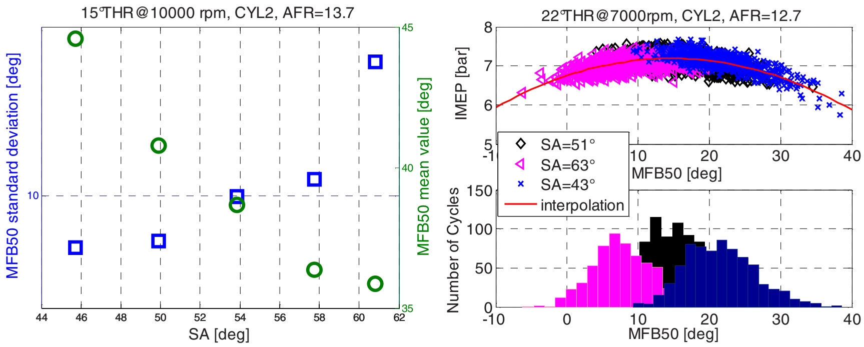

Figure 2(a): race engine part load-high speed behavior; Figure 2(b): general IMEP trend and MFB50 distribution

Once again, the approach based on the distribution would be inconsistent with results based on mean values: this can be explained considering the effect that the combustion phase standard deviation has on IMEP mean value.

Figure 2 (b) shows how the IMEP distribution of the whole data set can be fitted with a polynomial regression, while the MFB50 values competing to a given SA setting (35°) can be represented by means of a normal pdf.

The previous considerations lead to the conclusion that an accurate determination of the Optimal SA requires the trend of IMEP as a function of SA: nonetheless, the approach based on the distributions can be used during the first sweeps, when only a few points in the plane IMEP-SA are available. In fact, a first estimate of the optimal SA could be carried out right after the first sweep, observing how the distribution of the cycles covered during the sweep for the considered breakpoint are placed in the plane IMEP-MFB50. The optimal MFB50 is evaluated as the abscissa of the maximum IMEP distribution, then the corresponding optimal SA is computed based on the relationship between MFB50 and SA in the experimental data.

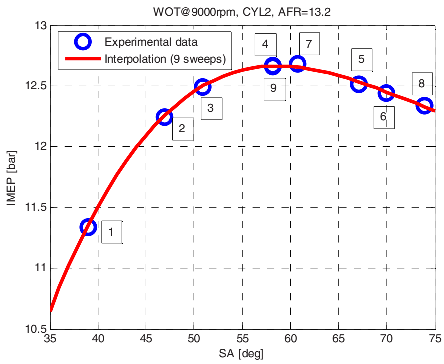

Figure 3: building of the bell-shaped IMEP-SA curve sweep by sweep

As the number of sweeps becomes high enough to give reliable results in the interpolation of the points representing mean IMEP and SA values in the plane IMEP-SA (figure 3), the optimal evaluation can be switched to this method.

The integration of the two methodologies assures at the same time a fast estimation of MBT spark advance, and an accurate evaluation at the end of the calibration process.

3.2. Knock evaluation

Even the simplest SA calibration approach must be multi-objective, since excessive knocking conditions must be avoided. In fact, the SA region explored during the calibration could involve heavy knocking conditions: in order to eliminate the risk of damaging the engine, the index used for IMEP maximization must be joined by another, sensitive to knock intensity, finally allowing the calibration process to reach optimal and safe SA values.

Many indexes can be found in the literature ([26-29]) to diagnose the presence of knocking phenomena, based on the in-cylinder pressure signal: most of them use the amplitude of the typical high-frequency pressure oscillations, that can be considered the signature of knocking combustions. In the present work one of the most commonly used indexes, the MAPO, is adopted for the sake of knock diagnosis:

$$MAPO = \max \left| p_{filt} \right|_{\vartheta start}^{\vartheta end} \tag{1}$$

Since knock is a stochastic phenomenon, the relationship between MAPO intensity and the corresponding SA setting is analyzed on a statistical basis: the same analysis can be applied to different indexes.

As suggested in [29], the distribution of knock indexes can be represented by means of a lognormal probability density function. This information can be used in order to estimate the highest values that the index could assume, given the shape of the actual distribution: the estimation can be based on a limited number of engine cycles, in order to reduce the calibration time (and, as a consequence, the potential damages to the engine during the calibration process).

The cumulative probability density function corresponding to the lognormal pdf fitting the MAPO distribution allows estimating the probability that MAPO values are lower than a given threshold:

$$L(x) = \int_0^x l(x)dx = P(MAPO < x) \tag{2}$$

The estimated cumulative probability density function can finally be used to define the value of MAPO corresponding to a given probability. This parameter can be considered as significant of knock intensity: choosing a 98% probability as a reference, means tracking the value of the 98th highest index out of 100 cycles. The parameter MAPO98, corresponding to the 98% probability, has then been used in the calibration process. The percentile method has been introduced by Leppard in [28]: the present technique applies the same approach, using the lognormal fitting in order to decrease the number of cycles in the sample used to evaluate the probability. A significant sample of engine cycles necessary for the evaluation of MAPO98 could involve many hundreds of elements: using the lognormal pdf fitting approach allows decreasing the number of elements in the sample, without deteriorating the estimate.

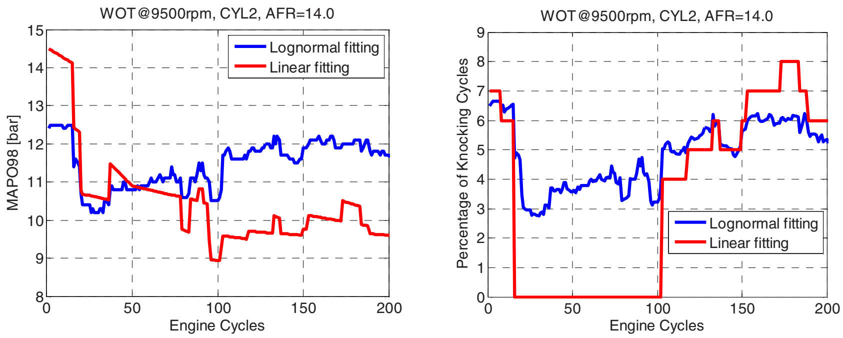

Figure 4(a): estimated MAPO98 using 100 cycles; Figure 8 (b): percentage of engine cycles evaluated with/without pdf approach

Figure 4 (a) shows how using the probability density function the MAPO98 range can be reduced with respect to an evaluation based on a linear interpolation of sorted MAPO indexes, allowing a clearer identification of knock intensity, even with a statistical samples of just 100 cycles.

Another possible knock intensity index is the percentage of engine cycles exceeding a given threshold: once again, in order to improve the index dynamics, the number of engine cycles in the statistical sample should be small, but this choice would affect the percentage reliability. Figure 4 (b) shows how this type of analysis benefits of the knock indexes pdf approach. The percentage of knocking cycles directly evaluated on the basis of experimental data is irregular, ranging from 0% to 8%, while the trend calculated by means of the lognormal probability density function fitting the experimental data, is included between 2.7% and 6.7%.

3.3. Knock phenomenological model

The calibration operation proceeds with successive speed sweeps where SA is changed searching for the optimal condition: knock occurrence should be taken into account in the definition of the SA setting that will be used for the next speed sweep.

In order to estimate the evolution of MAPO98, avoiding excessive knock intensity, an interpolation of the knock intensity index values as a function of actuated SA is carried out. The interpolating function is exponential:

$$MAPO_{98} = A \cdot e^{B \cdot SA} + C \cdot e^{D \cdot SA} \qquad (3)$$

The expression (7) allows tracing the plot reported in Figure 5 (a): it is possible to estimate the value of SA that will lead to unacceptable knock intensity. The estimate will start as the number of sweeps will be high enough, therefore the SA will be kept to safe values in the first few speed ramps. After that, the estimate will be updated sweep after sweep, avoiding the application of dangerous SA values.

At the end of the calibration process, the model will be robust enough to represent the engine knock tendency as a function of SA, thus it is used to determine acceptable SA values, with a safe margin with respect to a knock intensity threshold.

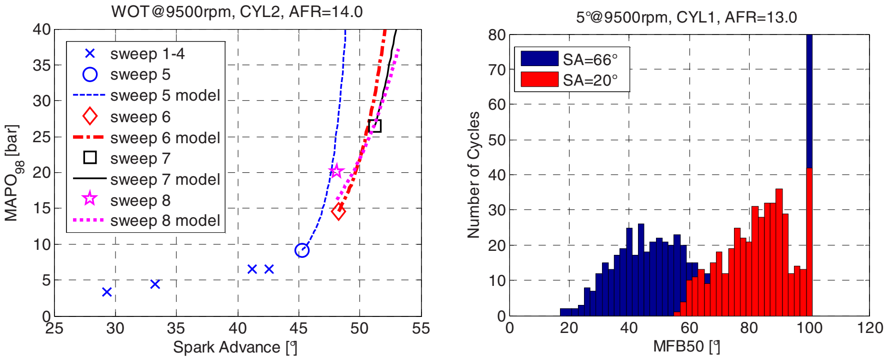

Figure 5 (a): knock tendency estimation; Figure 6 (b): MFB50 distributions under misfiring conditions

The same approach is used during the calibration stage, when the model changes from sweep to sweep, as it can be seen in Figure 5 (a). In this case a higher threshold level is used, to allow exploring knocking conditions, avoiding at the same time excessive thermal stress.

3.4. Misfire evaluation

During calibration operations missing combustion may occur, due to excessively high or low spark advance (low load-high speed conditions). Misfiring combustions can be automatically detected, using parameters such as IMEP, MFB50, or CHR. An automatic calibration system should avoid using SA causing a high misfire percentage: once a given threshold has been exceeded, the calibration should not insist in the same direction. However, the system must be able to determine whether the cause of the missing combustion is an excessively high or low SA.

This operation is carried out with the observation of the combustion phase: if the SA is too high, some combustion may be missing, other cycles could be slightly advanced. On the contrary, if misfires take place due to low SA values, all the cycles will be retarded. Figure 5 (b) shows haw it is possible to distinguish between the two conditions.

Once the critical condition have been detected, the system will be able to avoid applying higher (or lower) SA for the considered breakpoint and the considered cylinder. As shown for the knock indexes, a statistical/phenomenological model can be used to predict misfiring percentage for SA values that has not been tested yet: however, misfiring phenomena are less critical for the engine, so this step can be skipped.

3.5. Definition of new SA lookup table

At the end of a speed sweep, combustion data can be analyzed, according to the considerations shown in previous paragraphs. After the combustion analysis step, the following information are available:

- optimal SA
- knock intensity as a function of SA
- misfire tendency

The strategy leading to define SA values that will be used for the next sweep depends on the calibration requirements: obviously, if the objective is to reach the maximum IMEP in the lowest number of sweeps, the choice should be to actuate SA values leading to a robust optimal SA evaluation. In some cases (torque control by means of SA) it could be useful to trace the entire bell-shaped curve of IMEP as a function of SA: in this case a higher number of sweeps is necessary. A possible solution to manage the SA variation sequence is to define an array of SA variations with respect to the optimal predicted SA. Depending on the calibration requirements (low number of sweeps, or high resolution on the bell-shaped IMEP-SA curve), the array of SA variations will have less or more elements. Since optimal SA varies from sweep to sweep, it could happen that similar values of SA are requested in different sweeps. In this case, a different value, filling the empty space between two subsequent SA values is actuated.

The process is carried out cylinder by cylinder, breakpoint by breakpoint.

4. RESULTS

The methodology has been tested on the test-bench on a 4 cylinder motorcycle engine. The calibration technique has been implemented on a programmable real-time system, capable of performing combustion analysis, best SA estimation and communication with the test-bench controller (via CAN) and with the ECU (via Ethernet).

The first sweep has been run with a safe SA value, then all the subsequent SA actuations have been defined with respect to the estimated MBT setting. A total of nine speed sweeps have been considered sufficient to test the calibration method efficiency.

Figure 6 (a) shows IMEP as a function of SA, forming the typical bell-shape trend. Figure 6 (b) shows that the estimated MBT Spark Advance changes slightly during the calibration operation, finally settling to around 51° after the fifth ramp.

It is important to point out that for the first four sweeps the estimation of MBT Spark Advance is carried out according to the IMEP-MFB50 distribution (Figure 2 (b), upper plot), while for the following sweeps the IMEP-SA bell-shape curve (Figure 3) is preferred. The switch from one approach to the other is regulated by plausibility checks.

The sweep numbers reported in the plots allow explaining the strategy of SA variation applied over the speed sweeps: the first value has been chosen according to previous experience, as a safe value to start with. All the subsequent values are chosen with respect to the estimated MBT, according to the expression:

$$SA_i = SA_{MBT} + \Delta_i$$

$$\Delta_i = -10;-4;0;+2;+8;+12;+16;+2 \quad (4)$$

Figure 6 (c) shows the SA values actuated for each one of the speed sweeps performed during the calibration process.

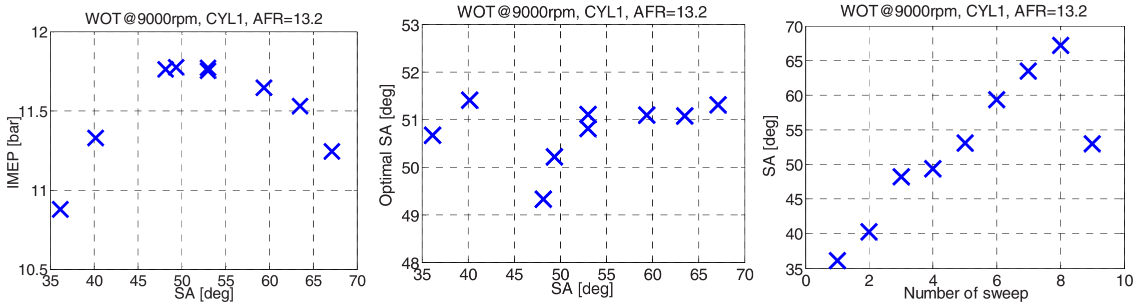

Figure 6 (a): IMEP-SA curve; Figure 7 (b): estimated MBT SA; Figure 7 (c): actuated SA

Figure 7 shows the result of the calibration procedure for a load breakpoint: every single engine speed breakpoint of each cylinder has been optimized. The complete calibration procedure is carried out in about ten minutes.

The optimal SA variations that can be observed throughout the engine speed range can be attributed to variations in the combustion characteristics (ignition time, combustion speed, etc.) taking place changing engine speed with fixed load.

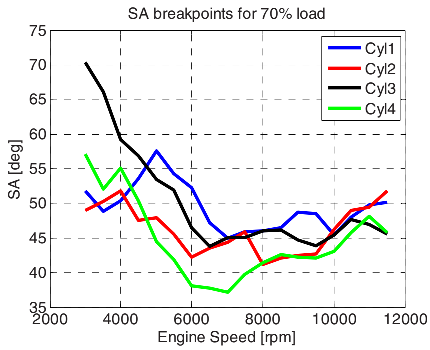

Figure 7: output of the calibration procedure

5. Conclusions

The paper describes a methodology aimed at the calibration of Spark Advance in SI engines. The calibration target is knock-free IMEP optimization. Operations are carried out on the test bench in dynamic conditions, during engine speed sweeps at constant load. At the end of every sweep optimal SA is estimated and new SA settings are uploaded to the ECU.

The definition of optimal SA is managed in two steps: initially, the IMEP-MFB50 distribution is analyzed, searching for maximum IMEP combustion phase, then IMEP-SA bell-shaped curve is taken into account, as the number of sweeps (i.e., different SA actuations) allows interpolating the performance curve. Statistical analyses involving actual knock index distributions interpolation with lognormal probability density functions, are applied in order to limit the number of engine cycles necessary to draw conclusions (knock tendency) about a given SA setting. As regards knock limits, an extrapolation of the statistical knock index is performed, in order to avoid excessive knock intensity during the sweep. Misfire tendency is also taken into account, leading to maximum or minimum acceptable SA values.

The methodology has been tested in real-time on the test bench, showing that a complete calibration operation for a fixed load breakpoint can be carried out in ten minutes.

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