

Knock and Cycle by Cycle Analysis of a High Performance V12 Spark Ignition Engine. Part 1: Experimental Data and Correlations Assessment

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ABSTRACT

In this paper, a high performance V12 spark-ignition engine is experimentally investigated at test-bench in order to fully characterize its behavior in terms of both average parameters, cycle-by-cycle variations and knock tendency, for different operating conditions. In particular, for each considered operating point, a spark advance sweep is actuated, starting from a knock-free calibration, up to intense knock operation. Sequences of 300 consecutive pressure cycles are measured for each cylinder, together with the main overall engine performance, including fuel flow, torque, and fuel consumption. Acquired data are statistically analyzed to derive the distributions of main indicated parameters, in order to find proper correlations with ensemble-averaged quantities. In particular, the Coefficient of Variation (CoV) of IMEP and of the in-cylinder peak pressure (p_{max}) are correlated to the average combustion phasing and duration (MFB_{50} and $\Delta\theta_b$), with a good coefficient of determination. In addition, a high-pass-filtering technique is used to derive the cycle-by-cycle scattering of the Maximum Amplitude of Pressure Oscillation (MAPO) index. A similar statistical analysis is carried out to derive the log-normal distributions of the MAPO index and a methodology to assess a proper knock threshold is applied to identify the presence of knocking combustion. The above data represent the prerequisites for the implementation and validation of an advanced 1D model, described in Part 2, taking into account cycle-by-cycle variations, and finally aiming to identify the knock-limited spark advance on a completely theoretical basis.

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INTRODUCTION

It is widely recognized that cycle-by-cycle variations (CCV) largely affect Spark-Ignition Internal Combustion Engine (SI-ICE) performance. As known, consecutive engine cycles are characterized by a different evolution of the combustion process, resulting in different pressure traces. CCV are important because they greatly affect both engine performance and calibration [1].

Concerning engine performance, since the optimum spark timing is set for the average cycle, *faster-than-average* and *slower-than-average* cycles are not properly phased, resulting in power and efficiency losses. Moreover, a too large level of cyclic variation has a negative impact on the vehicle drivability [2] and leads to increased levels of pollutant emission, fuel consumption and noise, due to engine roughness [3,4]. CCV drawbacks are even more felt at low load, and for SI-ICEs operating with lean fueling and high EGR rates, where a more difficult mixture ignition and a slower flame propagation occur. Concerning the engine calibration, CCV also pose several problems at high load, when knocking phenomena may

establish. As known, knock arises when air/fuel charge molecules that burn late during the combustion process (end-gases) spontaneously ignite before they have been reached by the propagating flame front [1,5]. The experimental identification of the Knock-Limited Spark Advance (KLSA) is a complicated task, requiring the measurement of different instantaneous pressure cycles, at a high crank angle resolution. In addition, a careful treatment of the measured data must be performed to extract the high frequency components from each instantaneous pressure cycle [6,7]. Typical high frequency knock signatures are related to the combustion chamber resonance frequencies [8,9], excited by the knock-induced pressure wave propagation. Amplitudes of the high frequency filtered pressure are used to define a great variety of knock indices [10, 11, 12, 13]. However, whichever is their definition, they are affected by the pressure sensor type, by its position inside the combustion chamber [6,12], and by the engine operating conditions [14, 15, 16].

CCV have been observed and intensively studied over the last decades and different causes have been identified. They are mainly due to the random differences in the in-cylinder spatial distribution of mean flow, turbulence, air-to-fuel ratio, and residual content, especially near the spark plug. They are also affected by spark discharge characteristics. All these phenomena are strongly coupled, depending on the engine geometry and operating conditions, and are poorly predictable at the stage of engine design. From an experimental point of view, the study of CCV is typically based on the acquisition and post-processing of consecutive in-cylinder pressure traces (ranging from 300 up to 2000 cycles, [2]). Moreover, in-depth analyses of the origins of the phenomenon have been performed through optically accessible engines [17, 18, 19, 20] and by 3D-CFD simulations [21,22].

Cyclic variability can be well characterized in terms of Coefficient of Variation (CoV)¹ of pressure-related parameters (IMEP and p_{max}) and combustion-related parameters (MFB_{50} and $\Delta\theta_b$) [23]. Many authors related CCV to parameters which directly affect combustion speed, such as the equivalence ratio, the spark advance, or the fuel type. Pundir et al. [24], as an example, stated that the $CoV_{p_{max}}$ was minimum when stoichiometric mixtures were adopted, while variations in the equivalence ratio inevitably lead to increased CCV. Hassaneen et al. [25] tested an 8-cylinder natural gas SI engine and found that $CoV_{p_{max}}$ and CoV_{IMEP} risen by 33% as the equivalence ratio decreased from 1 to 0.6. Abraham and Prakash [26] studied the impact of spark event on CCV with three different timings: 26, 22 and 16 CAD BTDC. The results showed that $CoV_{p_{max}}$ increased when the spark was retarded (16 CAD) and reached a minimum at an ignition timing of 26 CAD BTDC. The above finding was confirmed under both part and full load operation. The studies by Young [27] underlined that CCV were minimized at the ignition timing that realized the Maximum Brake Torque (MBT). Ozdor et al. [28] studied CCV for a four-stroke, 4-cylinder engine for various speeds and excesses of air, always maintaining the spark timing at MBT. The results showed that CCV were minimum for a stoichiometric mixture, while the engine speed only exerted a negligible effect. Maurya and Agarwal [23] indeed investigated the relations among combustion phasing, combustion duration and the CoV_{IMEP} for two different fuels (gasoline and ethanol) and for HCCI combustion. It was observed that longer combustions and late phasing involved higher IMEP variations for both fuels and a second order polynomial correlation between CoV_{IMEP} and combustion duration was developed.

In the present paper, a high performance 12-cylinder naturally aspirated SI engine is experimentally and numerically analyzed with main emphasis on CCV and knocking phenomena. The paper is organized in two parts: the present part one is focused on the experimental characterization of CCV and on the experimental identification of the KLSA at full load. Different operating conditions and various spark timings are investigated, starting from knock-free operation up to intense knocking conditions. An “indicated analysis” of the acquired pressure cycles is firstly carried out, aiming to

identify the cycle-by-cycle distributions of the pressure-related and combustion-related parameters. They are then correlated with ensemble-averaged quantities. A “knock analysis” is then performed to derive the Maximum Amplitude of Pressure Oscillation (MAPO) for the overall set of acquired pressure cycles. A proper threshold level is defined to establish the KLSA realizing a 2% of cycles above the threshold in each condition.

The part two of the paper will be indeed focused on the numerical simulation of the same engine. The developed correlations will be employed within a refined 1D model for the simultaneous computation of the *average* and representative *faster-than-average* and *slower-than-average* cycles, in each tested condition. With reference to the estimated *faster-than-average* cycle, the solution of a kinetic scheme in the unburned gas zone allows to predict the KLSA, utilizing the same experimental threshold level. A very good agreement with experimental data will be finally shown in Part 2 on overall performance, average pressure cycles, CCV and KLSA.

EXPERIMENTAL SETUP

Main characteristics of the engine under investigation are listed in Table 1. It is a naturally aspirated 12-cylinder engine, equipped with port fuel injectors. It is installed at the test bench and experimentally analyzed in different operating conditions with the aim to collect the main overall performance such as the brake power, brake torque, brake specific fuel consumption, fuel flow rate, etc. Each cylinder is equipped with a dry pressure transducer located between the intake and exhaust valves. As known, a dry sensor may be affected by a certain uncertainty and instability with respect to a wet one, especially during the expansion phase, when the sensor undergoes relevant thermal shocks. However, in the proposed experimental activity dry sensors are selected because of their ease of installation, not requiring a coolant (water) circuit. An optical encoder is used to trigger the acquisition of the in-cylinder pressure signals. The measured signals are processed by a charge amplifier and by an analogic/digital converter. The digital output is elaborated by the indicating software for the computation of the main indicated and combustion parameters (pressure-volume diagram, IMEP, maximum in-cylinder pressure, PMEP, mass fraction burned, knock parameters, etc.) in real time. The acquisition system also provides as an output the statistical indices of the measured data.

Table 1. Engine main features

Unit Displacement	541.54 cm ³
Bore, Stroke, Connecting Rod	95, 76.4, 145.8 mm
Compression ratio	11.8:1
Number of Cylinders and Valves	12 – 4
Maximum Torque	697.6 Nm @ 6000 rpm
Maximum Power	507.5 kW @ 7000 rpm

In particular, measurements were carried out at an engine speed ranging from 2000 to 7000 rpm at full load. More limited part-load analyses were performed, as well. For each speed, a 2 CAD spark

1. CoV of a distributed parameter P is defined as the ratio between the standard deviation, σ_P , and the average value, P_{av} : $CoV_P = \frac{\sigma_P}{P_{av}} \cdot 100$

timing sweep was actuated, starting from a reference spark advance (Base SA) and following the test matrix consisting of 63 operating points, reported in Table 2. The Base SA corresponds to a first evaluation of the SA at the knock limit identified by heuristic procedures, based on operator experience at the test bench. A more precise identification of the KLSA is performed in the Knock Analysis paragraph. The equivalence ratio is enriched increasing the engine speed due to some limitations related to knock occurrence and constraints on maximum allowable temperature at the catalytic converter. For each speed, regardless the load and spark timing, the air-to-fuel ratio is maintained at an almost constant level.

Table 2. Test matrix

Speed, rpm	BMEP, bar	Spark Advance, CAD BTDC						
		+6	+4	+2	Base	-2	-4	-6
2000	WOT	+6	+4	+2	Base	-2	-4	-6
3000	WOT	+6	+4	+2	Base	-2	-4	-6
4000	WOT	+6	+4	+2	Base	-2	-4	-6
5000	WOT	+6	+4	+2	Base	-2	-4	-6
6000	WOT	+6	+4	+2	Base	-2	-4	-6
7000	WOT	+6	+4	+2	Base	-2	-4	-6
1000	5	+6	+4	+2	Base	-2	-4	-6
2000	6	+6	+4	+2	Base	-2	-4	-6
3000	10	+6	+4	+2	Base	-2	-4	-6

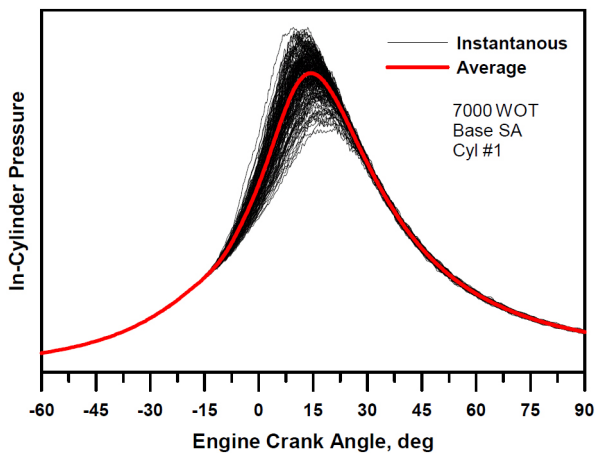


Figure 1. Instantaneous and average in-cylinder pressure cycles at 7000 rpm and Base SA

In each tested point, 300 consecutive pressure cycles are acquired for each cylinder, with a sampling resolution of 0.2 crank angles. As an example, Figure 1 shows the sequence of in-cylinder pressure cycles, superimposed to the ensemble-averaged one, recorded at 7000 rpm, for the base SA (cyl. #1). Post-processing of the above data allows to derive the IMEP and p_{max} distributions, together with the mass fraction burned, synthesized in terms of crank angles of 10%, 50% and 90% (MFB_{10} , MFB_{50} and MFB_{90} , respectively). Due to inaccuracies in the determination of the MFB_{90} along the final combustion tail, the usual definition of combustion duration ($MFB_{90} - MFB_{10}$) is here conventionally replaced by $\Delta\theta_b = 2 (MFB_{50} - SA)$.

INDICATED ANALYSIS

In this section, CCV are analyzed in order to highlight their relationship with main engine operating parameters, such as the engine speed and the spark timing. As already pointed out, CCV are quantified in terms of CoVs of pressure-related parameters, i.e. IMEP and p_{max} . However, while CoV_{IMEP} clearly affects the engine drivability, a more relevant role is played in this study by $CoV_{p_{max}}$, since it exerts a direct influence on knock occurrence, as more deeply discussed in the next section. In Figure 2a, the IMEP distribution is shown with reference to pressure cycles reported in Figure 1. The distribution, as expected, reveals a Gaussian behaviour, with standard deviation and CoV values below the limits accepted by the manufacturer. The latter are even more reduced for an advanced spark timing (Base SA-6, Figure 2b). The above finding, mainly due to higher in-cylinder pressure and temperature during combustion, confirms previous observations available in the literature. Despite of the reduced CoV_{IMEP} , high cycle-by-cycle variations of the in-cylinder peak pressure occur in the same operating condition (Figure 3). As before, however, a slightly narrow p_{max} distribution is obtained for an advanced spark timing (Figure 3b).

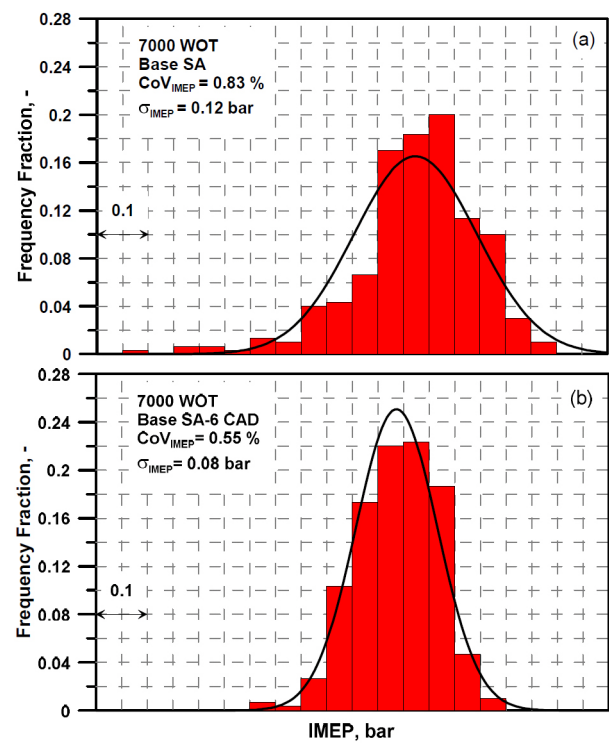


Figure 2. IMEP distribution at 7000 rpm: (a) Base SA. (b) Advanced SA

A more clear overview of the SA impact on IMEP and p_{max} dispersions, (vertical dots), can be taken from Figure 4 and Figure 5, referring to full load operation at 7000 rpm. Related CoVs and average levels are also reported as continuous lines. The SA realizing the MBT, can be easily determined as shown in Figure 4, and, correspondingly, CoV_{IMEP} attains approximately its minimum. It is moreover confirmed that p_{max} dispersion (Figure 5) is much higher than IMEP one, for each tested SA. In addition, a delayed SA (SA+6) determines a $CoV_{p_{max}}$ increase.