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# Knock-limited spark angle setting by means of statistical or dynamic pressure based methods

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ABSTRACT

In spark-ignition engines, knock is a very rigid constraint because it prevents the use of optimal spark timing and it limits the compression ratio and/or the boost pressure. Unfortunately, during engine development, it is not easy to detect the transition through borderline knock. Therefore, large "safety limits" could be adopted in spark timing setting. That penalizes the engine fuel conversion efficiency.

This paper deals with the effectiveness of two knock quantification methods. Both methods are based on the analysis of the in cylinder pressure trace. The first method determines knocking combustions by means of a threshold value. This threshold is set by the statistical analysis of a knock-free engine operating point. The second method does not need any a priori threshold setting to distinguish knocking combustions from non-knocking combustions. It dynamically resolves the knock intensity of an engine cycle within the same cycle.

Experimental analyses show that both methods are able to detect knock occurrence in spark-ignition engines. In particular, the dynamic method can be a simple and reliable tool useful for setting knock-limited spark angle during engine development.

## 1. Introduction

The purpose of reducing fuel consumption and green-house gas emissions leads to the development of downsized, turbocharged engines characterized by more and more high compression ratios [1–4]. Thus, modern internal combustion engines experience very high in-cylinder pressure and charge temperatures when achieving high loads. This raises knock risk in spark ignition engines [5–7].

Nowadays, it is appropriate to distinguish between knock and super-knock. Under extreme conditions, super-knock is the result of the pre-ignition of the charge. Probably, this phenomenon is the main obstacle to the development of both advanced spark-ignition engines [8–10] and new HCCI engines [11–13]. However, for conventional spark-ignition engine, knock also is an extremely stringent constraint since it prevents the use of optimal spark timing, high compression ratio or high boost pressure [14]. Besides, in boosted engines this phenomenon can occur even at the maximum speed characterizing the engine operating range [15].

It is generally accepted that knock occurs when some portions of the end gas attain the conditions to spontaneously ignite prior to the flame arrival [16]. The sudden heat release associated to the end-gas auto-ignition may produce a sharp increment in local pressure that propagates throughout the chamber in the form of pressure waves. Resonating through the combustion chamber, the high-speed pressure waves create the sound which gives knock its name.

Pressure waves of substantial amplitude can exert sizeable actions on the surroundings of the combustion chamber. Therefore, under certain conditions, knock occurrence can result in severe permanent engine damages [14]. Actually, knocking phenomena do not indicate imminent engine failure. If infrequent, moderate levels of intensity produce little or no damage [17]. Vice versa, sustained knock events can damage piston crown, piston rings, head gasket and exhaust valves.

In spark-ignition engines, knocking is kept under control by retarding the spark timing relatively to the optimal one [18]. Unfortunately, it is not easy to grasp the transition from a non-knocking state to a knocking state [19], i.e. to identify the so called knock onset limit. Therefore, often, engine manufacturers operate with large "safety margins" which may significantly penalize the thermal efficiency of the engine.

Therefore, it is important to establish criteria able to objectively quantify the knock intensity of an engine operating point. In this way, the engine developer can adopt limited spark angle actually corresponding to borderline knock.

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A lot of criteria have been already proposed to detect and quantify knock occurrence in internal combustion engines [20,21].

In the mass-produced engines, knock is usually detected by measuring the vibration that pressure oscillations transmit to the engine block [22]. In laboratory tests, methods based on the measurements of in-cylinder pressure oscillations are usually preferred because they grasp the primary effect due to knock occurrence. Pressure data can be processed in both the time and frequency domain [21,23–27] or by using discrete wavelet transform [28]. Alternative methods as gas ionization analysis [29], optical analysis [30], heat transfer rate analysis [31] have been also investigated.

Unfortunately, detection methods need tuning to match the engine. Some thresholds have to be defined so to identify the knocking engine cycles [21–24,32]. These knock threshold values should not only be adapted to a specific engine, but also to operating conditions. Several trial analyses should be made at a number of speed and load conditions, running the engine into borderline audible knock [21]. Some time, empirical values are used [6]. The threshold selection is a focus point in estimating knock conditions for engine operation.

In previous works, two methods have been proposed to detect and quantify knock occurrence in spark-ignition engines [33,34]. Both methods are based on the analysis of the in cylinder pressure and they can be useful to quantify knock occurrence during engine development.

The first method is based on a solid statistical analysis. This analysis allows setting an a priori knock threshold able to distinguish between knocking cycles and free knock cycles. The second method is a dynamic method. The knock intensity of an individual cycle is resolved within the same cycle by comparing the maximum value of the knock pressure during the first combustion phase to that characterizing the remaining part of the combustion. Compared to the other approaches mentioned above, it does not need the setting of a predetermined threshold able to distinguish between knocking events and non-knocking events. Consequently, this method is easy to use during engine development tests.

In this work, the effectiveness of these methods is further discussed by analyzing an extensive set of experimental data. Focus is on the detection of the spark advance determining the occurrence of trace of knock in an engine operating point.

## 2. Experimental setup

Steady state tests (Table 1) have been performed on a downsized, port fuel injection spark-ignition engine featuring four cylinders mounted in a straight line. The total displacement is 1368 $cm^3$.

Both the engine and the experimental setup have been widely described in Ref. [34]. Briefly, the engine was coupled to an eddy current dynamometer (Fig. 1). An AVL Puma 5.3 system has been used for test control and data acquisition. A fuel balance (inaccuracy less than 0.5%) measured the fuel consumption, while a Horiba UEGO sensor (inaccuracy less than 4%) has been used to monitor the air excess ratio.

During the tests both the injection timing and the ignition timing have been opportunely tuned by means of an on-line programmable engine control unit.

In each test case, engine speed, manifold absolute pressure and air excess have been kept constants while the spark timing has been advanced from free knock operating conditions to audible knock operating conditions.

The in-cylinder pressure trace of the first cylinder has been acquired by means of a flush-mounted miniaturized quartz transducer (AVL GM14D, sensitivity 19pC/bar). A crankshaft encoder (AVL 364) provided the crank angle reference for the measurements. A multichannel indicating system AVL Indimeter 620 has been used for data acquisition and signal conditioning, while an IndiCom software has been used both to control measurements and for data post-processing. The pressure curve position has been set by means of a thermodynamic correction of the compression phase; a polytropic exponent equal to 1.32 has been considered. For every engine operating point, five hundred engine cycles have been measured. Data have been sampled at 0.2 crank angle degree intervals. A handmade tool developed by the author within the Matlab environment has been used to process the data.

Other measurements (i.e. fuel consumption, intake manifold absolute pressure and temperature) are the average results of acquisitions made over a period of 60 s. Data have been measured only when the temperature of the exhaust gas was constant (steady conditions).

## 3. Knock quantification

The local sharp pressure gradient caused by the auto-ignition of the end-gas leads to resonant pressure waves in the combustion chamber. The subsequent local oscillations, which can be observed clearly on the cylinder pressure curve (Fig. 2), provide a reliable indication of the occurrence and severity of the knock event.

Flat cylindrical cavities are characterized by radial and circumferential resonant modes, while axial modes are negligible. For each vibration mode, the amplitude of the acquired signal depends on both the amplitude of pressure disturbance and the position of the transducer relative to the nodal and anti-nodal surfaces [23].

Pressure waves travel at the local speed of sound, thus size and shape of the chamber together with the gas temperature

**Table 1**
Test cases. Main Engine parameters.

| | Speed [rpm] | Manifold absolute pressure [bar] | Air excess [–] | Spark advance [°] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Engine torque [Nm] | | | | | | | | | |
| Test case 1 | 2000 | 1.08 | 1 | 7.5 | 8.5 | 9.5 | 10.5 | 11.5 | 12.5 | 13.5 | 14.5 | | |
| | | | | 108 | 109 | 109 | 110 | 112 | 112 | 112 | 111 | | |
| Test case 2 | 2500 | 1.11 | 1.14 | 12.5 | 13.5 | 14.5 | 15.5 | 16.5 | 18.5 | 19.5 | | | |
| | | | | 109 | 110 | 110 | 111 | 111 | 111 | 112 | | | |
| Test case 3 | 2500 | 1.25 | 1 | 3.5 | 4.5 | 5.5 | 6.5 | 7.5 | 8.5 | 9.5 | 10.5 | 11.5 | 12.5 |
| | | | | 127 | 130 | 133 | 135 | 136 | 138 | 139 | 142 | 142 | 143 |
| Test case 4 | 2500 | 1.45 | 1 | 1.5 | 2.5 | 3.5 | 4.5 | 5.5 | 6.5 | 7.5 | | | |
| | | | | 149 | 151 | 156 | 158 | 160 | 162 | 163 | | | |
| Test case 5 | 4000 | 1.05 | 1 | 15.5 | 16.5 | 17.5 | 18.5 | 19.5 | 20.5 | | | | |
| | | | | 108 | 109 | 109 | 110 | 110 | 110 | | | | |
| Test case 6 | 4000 | 1.38 | 0.85 | 8.5 | 9.5 | 10.5 | 11.4 | 12.5 | | | | | |
| | | | | 149 | 150 | 152 | 154 | 154 | | | | | |