

Investigation on Pre-Ignition Combustion Events and Development of Diagnostic Solutions Based on Ion Current Signals

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ABSTRACT

Pre-ignition combustions are extremely harmful and undesired, but the recent search for extremely efficient spark-ignition engines has implied a great increase of the in-cylinder pressure and temperature levels, forcing engine operation to conditions that may trigger this type of anomalous combustion much more frequently. For this reason, an accurate on-board diagnosis system is required to adopt protective measures, preventing engine damage.

Ion current signal provides relevant information about the combustion process, and it results in a good compromise between cost, durability and information quality (signal to noise ratio levels). The GDI turbocharged engine used for this study was equipped with a production ion current sensing system, while in-cylinder pressure sensors were installed for research purposes, to better understand the pre-ignition phenomenon characteristics, and to support the development of an on-board diagnostic system solely based on ion current measurements.

In this work, pre-ignition events induced by heavy knocking operation have been analysed. The focus was mainly on ion current signal real-time processing, and on the possibility to correctly and rapidly detect pre-ignition events. In a previous work, destructive effects of this kind of combustion on engine components had been described.

As shown in the paper, the development and implementation of an ion current based detection algorithm results to be very effective in identifying pre-ignition combustions, and it could allow an extremely fast reaction of the engine controller that can prevent further anomalous combustions once the first event has occurred. Moreover, pre-ignition phase information extracted from the ion signal and characteristic combustion angles obtained from pressure signal analysis are well correlated, further confirming the ion signal robustness and accuracy.

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INTRODUCTION

Pre-ignition combustion is extremely dangerous for the engine, as it induces high pressure levels and usually heavy knocking events. The excessive pressure can damage the connecting rod, while the increased heat transfer to the chamber walls may lead to seizure [1]. Increasing efficiency demand on SI engines results in higher pressure and temperature levels inside the combustion chamber, bringing the engine operation ever closer to anomalous combustion modes. The possibility of diagnosing pre-ignition can be fundamental in achieving higher efficiency or specific power, while safeguarding the engine. Once one or more pre-ignition cycles are detected, the Engine Control Unit has many ways to react (for example it can reduce the load, it can cut injection to one or more cylinders, it can vary the intake and exhaust valves overlap). Since there is no unequivocal definition of pre-ignition, a clarification is necessary: in this paper pre-ignition is a combustion process that

started before (and so not initiated by) the spark, independently of the combustion initiation cause. Such early combustion can be triggered by a hot-spot in the combustion chamber [2], by the compression ignition by oil contamination, or by glowing carbon deposits. The first mode is often called "surface ignition", while the two other modes are the most likely causes of the LSPI (Low Speed Pre-Ignition) [3, 4].

Ionization current sensing is based on the availability of radical ions in the combustion chamber during the combustion process [5, 6, 7]. Ion formation occurs in the flame front due to oxidation process and in the whole gas volume because of thermal dissociation. By applying a voltage difference between two electrodes and measuring the current, ion concentration in the gap volume between the electrodes can be evaluated [6, 7, 8]. In SI (Spark Ignition) engines, the electrodes are already present in the combustion chamber (spark plug

electrodes) and this technology results to be extremely reliable (and affordable) for this kind of engine. Ion current signal is taken from the ignition circuit, when it is not employed in generating the spark.

In [Figure 1](#), a typical ion current signal is reported for an engine cycle. The first part (called “Dwell” in [figure 1](#)) is the portion of the cycle during which the primary coil of the ignition circuit is powered. During this time, ion current signal is available but it is expected to be at zero level. As the primary coil is disconnected by a transistor, spark is generated between the spark plug electrodes, as a reaction in the secondary coil to the sudden current variation. During the spark (few hundreds of μ s) ion current signal is null, and after the spark end it shows the resonance response of the ignition circuit (signal ringing between -10 and 0°CA in [Figure 1](#)). The first peak after TDC, denoted in [figure 1](#) by letter “C” and commonly called “Chemical phase”, is due to the developing combustion kernel around the spark plug electrodes. The second peak, denoted by letter “T” (thermal phase) is due to thermal dissociation [\[5\]](#).

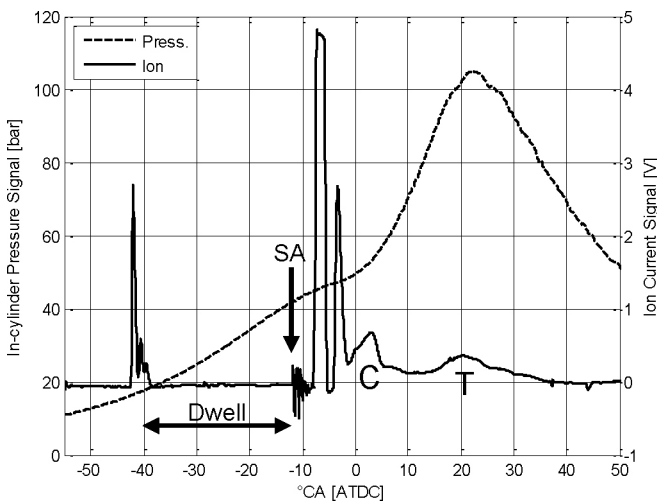


Figure 1. Typical behavior of the Ion current signal, superimposed to the corresponding in-cylinder pressure signal.

Ion current can provide many information about the combustion process, as reported by many authors [\[8, 9, 10\]](#), and excluding in-cylinder pressure sensors, being an expensive, short-lasting solution and as such not a feasible option for production, ion current sensing results in a reliable signal with a relatively high SNR.

Ion current signal is related to ion concentration (and it cannot be directly converted into pressure or temperature); moreover, it represents an extremely local information since it is necessary to substantially discard the hypothesis that the measured quantity is homogeneous in the combustion chamber (as it can typically be assumed for pressure signal).

Most of the literature is oriented on the analysis of the ion current signal during the active phase of the engine cycle, to diagnose knocking combustion, to identify peak pressure position, to quantify air-fuel ratio and to diagnose misfire [\[9\]](#). This work, instead, is focused on the capability of the ion current signal to diagnose pre-ignition [\[8, 10\]](#). Bounded nature of ion current signal

information is in general an intrinsically limiting factor for its interpretation, as it is blind in respect to what happens far from the spark electrodes. On the other hand, this limit gives great sensitivity to what happens close to the spark electrodes.

EXPERIMENTAL SETUP

Experiments were conducted on the test bench, on a 4 cylinder turbocharged GDI engine. Every cylinder was equipped for research purposes with 6045 A Kistler in-cylinder pressure transducers, moreover the engine was equipped with an ion current sensing system as standard production equipment. All in-cylinder signals, both pressure and ion current, were sampled at 200 kHz, and the main engine specifications are detailed in [Table 1](#).

Table 1. Engine specifications.

Compression ratio	9.4
Bore	86.5 mm
Displacement	1.93 liters
Fuel	RON 95

Reported data is relative to two different data sets, both at full load but at different engine speed (4500 and 6000 rpm). In the first test, pre-ignition events were triggered, in 3 cylinders, by heavy knocking condition, resulting in a run-away condition with detrimental effects on the engine. In the second test, sporadic pre-ignition events were observed in one cylinder, probably due to wear of the spark plug electrodes.

For both cases capability and sensitivity of the ion current signal in diagnosing pre-ignition combustions has been evaluated.

Test 1

Test 1 was conducted at 4500 rpm at full load. Heavy knocking condition was induced in cylinders 1, 2 and 3 by controlling the Spark Advance (SA). After 50-80 cycles (depending on the cylinder) some pre-ignition cycles occurred, alternating with normally ignited cycles. Then all cycles pre-ignited, in a self-sustaining mechanism that rapidly forced the start of combustion to migrate towards the early compression phase. [Figure 2](#) shows the time history of the crank angle value corresponding to 10% of mass fraction burned (CA10%MFB), which rapidly diminishes (symptom of more and more advanced, or early, start of combustion) when the combustion mode enters the pre-ignition region.

In a previous work [\[1\]](#), the pre-ignition sequence and the effects on the combustion chamber components have been thoroughly described. In [figure 3](#), ion current and pressure signals for some pre-ignition cycles are represented. Pressure traces, on the right, show cycles with different combustion phase and correspondingly increasing peak pressure, but above all, it is clear that these combustions started before the spark (SA). On the left, ion current signals of the same cycles are represented. Compared to the signal of [figure 1](#), all these cycles are characterized by a rising edge during dwell time, which indicates the presence of combustion.