

Characterization of Knock Tendency and Onset in a GDI Engine by Means of Conventional Measurements and a Non-Conventional Flame Dynamics Optical Analysis

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ABSTRACT

Gasoline direct injection (GDI) allows knock tendency reduction in spark-ignition engines mainly due to the cooling effect of the in-cylinder fuel evaporation. However, the charge formation and thus the injection timing and strategies deeply affect the flame propagation and consequently the knock occurrence probability and intensity. In particular, split injection allows a reduction of knock intensity by inducing different AFR gradient and turbulent energy distribution.

Present work investigates the tendency to knock of a GDI engine at 1500 rpm full load under different injection strategies, single and double injections, obtained delivering the same amount of gasoline in two equal parts, the first during intake, the second during compression stroke. In these conditions, conventional and non-conventional measurements are performed on a 4-stroke, 4-cylinder, turbocharged GDI engine endowed of optical accesses to the combustion chamber. Imaging in the UV-visible range is carried out by means of a high spatial and temporal resolution camera through a wide transparent window in the piston head allowing the view of the whole combustion chamber almost until the cylinder walls, to include the end-gas zones. Optical data are correlated to in-cylinder pressure-based indicated analyses and ion current data, on a cycle resolved basis. Normal flame front propagation before knock onset, end-gas auto-ignition and the effect of in-cylinder pressure waves of knock on the residual flame are deeply investigated. This synergic analysis is used to explore the effect of modulating injection on the charge formation optimization and the deriving improvement of combustion and reduction of knock tendency. Split injection reduces engine cycle-by-cycle variability with respect to the single injection case, all the others relevant parameters remaining unchanged. It is also able to increase the resistance to knock also changing relevantly the location of the knock onset.

A new methodology based on high temporal resolution optical diagnostics for the determination of the knock intensity and onset has been proposed. This procedure is focused on the cycle resolved analysis of the centroid of luminosity dynamics under the knock pressure waves. It allows the precise determination of knock onset timing and spatial location within the combustion chamber. Furthermore, the amplitude of the luminous centroid oscillation has been found in good agreement with the knock index obtained by in-cylinder pressure and the ion current based analyses.

This work and the proposed methodology can contribute to give a further insight to knock mechanism under real engine conditions.

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INTRODUCTION

The optimization of performance and emission of future internal combustion engine for passenger cars are imperative urgencies in order to allow their global use before their substitution with the electric vehicles [1]. In middle time, spark ignition engines will be a good compromise to this transition. Spark ignition engines have many excellent attributes. They are reliable, quiet, have excellent air utilization, and extremely clean with catalytic after-treatment. The gasoline direct injection (GDI) technology allows a better fuel economy than the port-fuel injection configuration through greater flexibility to load changes, reduced tendency to anomalous

combustions (especially abnormal or knock) and reduction of pumping and heat losses [2, 3]. Engine operating parameters, i.e. inlet pressure and temperature, spark timing, injection strategies, compression ratio, equivalence ratio and exhaust gas recirculation, must be optimized in order to achieve a high energy conversion efficiency [2,3].

Furthermore, charge stratification consents overall lean combustion with related additional advantages on gasoline consumption. The complete ignition of the charge, namely what can be considered as a regular fuel oxidation process, is strictly related to the quality of the charge formation [4, 5, 6]. In the spray-guided GDI configuration, the

fuel distribution near the spark plug must be controlled to achieve the desired equivalence ratio at ignition timing [7]. The wall guided configuration, instead, requires a proper injection phasing and optimal spray impact on the piston head. The secondary evaporation has a strong influence on the efficiency of the energy conversion and on pollutants emission [8, 9]. Inadequate mixture formation is indeed the most limiting factors of present GDI engines as it is the main source of abnormal combustion, in particular soot formation.

On the other side, direct injection, with the cooling effect of the fuel evaporating within the combustion chamber, can help to reduce knock tendency. It is well known that knock restricts the performance and the efficiency of a SI engine of a not negligible extent, since it limits the compression ratio, the spark advance and supercharging. Despite combustion has been widely studied for many years and knock the basic mechanism is clear, the understanding of the correlation between all the parameters involved is still far to be complete. Knock occurs when a portion of unburned air-fuel mixture auto-ignites and explodes in the end-gas zone not yet reached by the main flame front [10, 11, 12]. Moreover, emerging turbocharged SI engines can exhibit a new phenomenon: super-knock, or violent engine knock. Super-knock can damage engine components within only a few cycles. Because the events are sporadic and uncontrolled, it has been difficult to assess the causes and devise solution. Most of these abnormal combustion issues have been addressed with improved design or control schemes as well as fuel specifications. The role of the subdivision of injection in two or more events, in order to obtain performance improvement and emissions reduction, have been widely investigated [13, 14, 15, 16, 17]. In particular, the use of split injection allows the reduction of knock tendency and it can also contribute to super knock suppression [18-19].

Generally, knock detection is based on the analysis of time or frequency representations of the gathered vibration signal. However, available specifications of signal properties recorded during knocking combustion are of low coherence. The time of knock occurrence can be predicted quite well, but the severity of knock on a given cycle has eluded prediction. The most significant weakness of this method is very low signal-to-noise ratio, especially at high engine speeds, resulting from high background noise level. Moreover, confusion of the self-ignition phenomena on the basis of the pressure signal can arise from cycle to cycle variability. Optical and spectroscopic measurements have been used in these years having some significant advantages in comparison to vibration knock sensors or pressure measurements [10, 20, 21]. They give a not intrusive and high spatial resolution analysis even if an optical engine or a rapid compression machine must be employed.

Many index and methods for knock intensity evaluation and knock onset determination have been proposed by means of in-cylinder pressure analysis. However, these may suffer the influence of the transducer natural frequency and of the transducer shock period [22]. The ionization signal have been also used by many authors to study knock intensity. It was found to be sensible to different levels of knock and it can give detailed information as well as in-cylinder pressure sensor [23, 24, 25].

In this paper, a GDI high performance optical accessible multi-cylinder engine was used. Different knock regimes have been studied, high, medium and borderline knock, under engine condition close to real operation. The different knock conditions have been obtained by adopting the split injection against single injection and no other engine control parameter has been changed. The effect of the split injection in reducing knock tendency has been clearly highlighted. The in-cylinder pressure-based and the ion current signal analyses has been compared with high spatial and temporal resolution optical data on a cycle resolved basis. The flame front propagation preceding knock occurrence, end-gas auto-ignition and the effect of in-cylinder pressure waves on the residual flame have been observed and described in detail. From this, further insights into the nature of the auto-ignition process can be uncovered.

Knock intensity, onset location and timing have been studied through a new methodology based on high temporal resolution optical diagnostics. The new proposed procedure is focused on the cycle resolved analysis of the disturbance induced on the flames motion by the knock pressure waves. It allowed the precise determination of knock onset timing and spatial location within the combustion chamber. Furthermore, the amplitude of the component of the luminous centroid oscillation has been compared with the knock index evaluate through the in-cylinder pressure and the ion current based analyses. In the following, the good agreement within the different methods will be shown.

EXPERIMENTAL SET-UP AND PROCEDURE

Experimental Apparatus

The experimental apparatus included the following modules: an electrical dynamometer, an optical engine with a 2D digital imaging setup, a data acquisition system, and an electronic control unit. The electrical dynamometer allowed operating both in motoring and firing conditions that was appropriate to detect the in-cylinder pressure data and to explore the engine behavior in steady state conditions.

Table 1. Main features of the engine under study.

Item	Specification
Unitary displacement	435,5 cm ³
Stroke	80.5 mm
Bore	83 mm
Compression ratio	9.5:1
Max. boost pressure	2.5 bar
Valve Timing	Intake and Exhaust VVT
Exhaust Valve Opening	1° BBDC @ 0.15 mm lift
Exhaust Valve Closing	15° ATDC @ 0.15 mm lift
Max. power [kW]	147.1 @ 5000 rpm
Max. torque [Nm]	320.4 @ 1400 rpm

The optically accessible engine was a 4-stroke spark ignition direct injection engine, with 4-cylinder, and a displacement of 1750 cm³. It has a wall guided injection system with a 7 holes Bosch injector mounted between the intake valves and oriented at 70° with respect to the cylinder axis. The engine is equipped with a variable valve timing system in order to optimize intake and exhaust valve lift for

each regime of operation. The valve timing angles are referred to a valve lift of 0.15 mm. The engine was not equipped with any after-treatment device and it was fuelled with commercial grade gasoline. Details and specifications are reported in [Table 1](#).

An optical shaft encoder was used to transmit the crank shaft position to the electronic control unit. The information was in digital pulses, the encoder had two outputs, and the first was Top Dead Centre (TDC) index signal, which had a resolution of 1 pulse/revolution. The second was the crank angle degree marker (CDM) 1 pulse/0.1 degree. The engine was a 4-stroke and the encoder gave an output two TDC signal per engine cycle so to have the right crank shaft position. One pulse was suppressed via software. This allowed at 1500 rpm a temporal resolution of the digital to analog conversion of about 11 μ s, thus 90 kHz. This acquisition speed is enough to detect signals with frequency until about 45 kHz for the Nyquist sampling theorem.

A quartz pressure transducer was installed into the spark plug in order to measure the in-cylinder pressure with a sensitivity of 19 pC/bar and a natural frequency of 130 kHz. It had a pressure range of 0-200 bar and an overload capacity of 250 bar. The linearity was about $\pm 0.5\%$ of full scale output and the sensitivity drift over range at 200 ± 50 $^{\circ}$ C was $\pm 1\%$. The probe is flush-mounted in the combustion chamber in order to prevent possible effects of cavity. The central position in the spark plug allows an easy mounting but it would probably lead to undervalue some pressure oscillation modes. However, this position minimizes the influence of different knock onset locations and can give consistent and reliable data.

The engine was also equipped with a modified ignition system that allowed the detection of the cycle resolved ionization current without altering the ignition functions. The system includes a compact high energy pencil coil, a spark plug with a gap between electrodes of about 1 mm and an amplifier of the ionic current. This layout allows the same position for the in-cylinder pressure transducer and the ionization current sensor as they are both located in the center of the combustion chamber. Thus, these two measurements can be compared without any possible aliasing induced by a different position.

Optical Set-Up

Combustion evolution was analyzed by means of an optical accesses on the piston top, as shown in [Figure 1](#). The optical accessible engine was designed keeping the thermo-fluid dynamic configuration of the commercial engine in order to preserve, as much as possible, its performance. All the four cylinders were in firing condition and no skip firing strategies were used in order to obtain conditions as close as possible to real ones. This is very important especially for the investigated engine regime, i.e. under knocking, as thermodynamics of combustion chamber plays a key role.

Elongated pistons and cylinders were the main components designed to realize the optical access in the piston head. They essentially consisted of an elongated body that allowed the placement of the 45 $^{\circ}$ mirror in axis with the cylinder through a proper gap on the side surface. The piston has a transparent top surface realized by means of a sapphire window that assures the visibility of a wide portion of the combustion chamber. This solution created a slight modification of

the combustion chamber geometry with respect to the original one that was characterized by a small bowl. Nevertheless, it was expected that this alteration did not strongly influenced the investigated high load regime. The piston rings were substituted with teflon-bronze and carbon-bronze self-lubricating rings as the lubricated circuit was removed to prevent oil fouling of the mirror and of the optical windows. All of these components were designed to be easily assembled and disassembled during maintenance and optical windows cleaning operations. Details about the engine design can be found in [\[26\]](#).

Imaging and chemiluminescence measurements from ultraviolet (UV) to visible were performed by means of the optical experimental set-up shown in [Figure 1](#). The cycle resolved images were acquired through a high speed complementary metal oxide-semiconductor (CMOS) camera coupled with a UV-Visible Nikkor 78 mm lens. The camera had a maximal resolution of 1024x1024 pixel and a maximum frame rate of 1 million fps. A region of interest of 512 x 448 pixels and a frame rate of 50'000 fps were chosen to obtain a good accuracy in term of spatial and temporal resolution. This frame rate allowed particularly the visualization of the knock onset position and timing. It was also enough to detect knock oscillation at least until 25 kHz for Nyquist theorem, as said before.

An example of the bottom view is shown in [Fig. 1](#). Exhaust and intake valves are in the upper and lower region of the image, respectively, and the spark plug is located in the center. It is important to underline that flat piston allowed a wide view of the combustion chamber almost until the cylinder walls. This was necessary to the visualization of knock onset. Nevertheless, a small portion of the combustion chamber near the wall continue to be masked by the piston structure, see optical limit (red lines) in [Figure 1](#). However, as it will be shown later, the analysis of the centroid luminosity dynamic allows the identification the knock onset also when it is located out of the field of view.

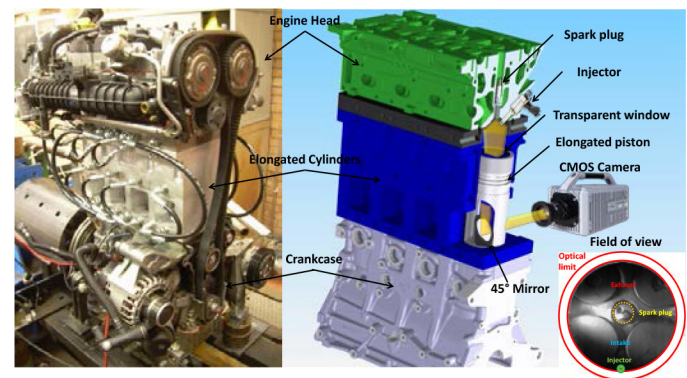


Figure 1. Experimental setup for optical investigation and detail of the combustion chamber field of view.

The exposure time is fixed at 17.21 μ s. A temporal resolution of about 0.18 crank angle degrees (CAD) and a spatial resolution of 0.15 mm/pixel were obtained. An AVL Indimodul records the TTL signal from the camera acquisition together with the signal measured by the pressure transducer, allowing to correlate the crank angles with

optical data detection. For all the optical measurements, the synchronization between the camera and the engine was made by the crank angle encoder signal through a unit delay.

Procedures and Methods

It is well known that knock conditions are characterized by high cycle to cycle variability, and the in-cylinder temperature could increase during the test. For both these reasons and in order to obtain comparable results within the different tests, all the measurements were carried out by adopting a procedure including an engine warm-up and a stabilization phase. The main control parameters were fixed under motored condition, and then the engine was started firing only 3 cylinders, excluding the injection in the optical one, in order to limit the fouling of the transparent window. In-cylinder pressure measurements were recorded on 200 consecutive engine cycles after about 50 cycles, as soon as the injection pressure was stable as well as the AFR at the target stoichiometric value. The analyses were carried out during the last 80 cycles. In this interval, the in-cylinder images of combustion were also recorded.

Generally, knock is characterized in terms of intensity and knock onset timing. Knock severity is related to the amplitude of pressure wave oscillations which may damage engine components, and so it depends on the amplitude of the high-frequency cylinder pressure oscillations. One of the most common measure of knock intensity is the maximum amplitude of high-or band-pass filtered pressure oscillation (MAPO) [23]. In this paper, knock intensity detected by means of in-cylinder pressure measurements was evaluated as MAPO. In-cylinder pressure has been filtered with a band pass-filter between 1 and 20 kHz. MAPO has been evaluated as the maximum amplitude of the filtered in-cylinder pressure's absolute value.

Knock onset is the crank angle of occurrence of the first explosion causing knock. The most intuitive and simple method for knock onset detection is the first crank angle where the in-cylinder pressure detaches from the low frequency component exceeds a predetermined threshold. It typically detects the KO late by up many CAD at typical engine speed [23]. Many other methods based on the first and third derivate of the pressure signals and also more complex have been proposed. In this work, knock onset have been precisely evaluated by means of optical diagnostics. It has been determined as the CA of the first explosion through the analysis of the centroid of luminosity dynamics.

The ionization current have been detected applying a DC voltage of about 200 V to the spark plug at the end of glow discharge phase. The voltage applied to the plug-gap generates an electrical field that promotes the movement of ions with a consequent production of a weak current. The current, in the range 30-300 μ A, is measured by means of an amplifier at the low-voltage side of the ignition coil. The ionization signal is characterized by two peaks. The first one is due to the formation of the flame kernel right after the spark. Chemi-ionization is considered the dominant mechanism of charged particle formation in this phase [24]. During flame front evolution the magnitude of the ionization signal reduces but as the pressure in the cylinder increases, the burned gases around the spark plug is ionized

again due to the high temperature caused by the combustion [25]. Thus, the second peak of the ionization signal is mainly related to the thermal ionization of the burned gas. In this phase, the combustion reactions around the ion sensor are finished, and the signals is strongly influenced by temperature and pressure variation induced by knock shock waves. Ion signals have been post-processed similarly the in-cylinder pressure in order to remove the low frequency harmonics through a band-pass filter between 1 and 20 kHz. Then, the maximum amplitude of the ionization signal (MAICO) has been evaluate as well as other authors [23]. ION signal has been filtered with a band pass-filter between 1 and 20 kHz in order to be comparable with the corresponding filtered in-cylinder pressure one. MAICO has been evaluated as the maximum amplitude of the absolute value of the filtered ION signal.

Moreover, a post-processing of the optical data was carried out by Labview™ of National Instruments to obtain geometrical information from each image, such as the flame front area and the radius. Additionally, the centroid of luminosity for each image was calculated as the brightness-weighted average of the x and y coordinates of all pixels. In this way it was possible to evaluate the cycle resolved centroid displacement during the normal combustion evolution, at the knock onset and during pressure wave propagation induced by detonation. The horizontal and vertical components of the centroid displacement in time domain were processed as well as the in-cylinder pressure and ionization current signals. A band pass filter between 1 and 20 kHz was applied in order to subtract the contribution of the slow movement. The maximum amplitude of the centroid luminosity oscillation (MACLO) was evaluate considering the module of the displacement obtained by the horizontal and vertical component of the centroid oscillation.

Finally, the frequency analysis of the centroid oscillation was carried out by applying a tone extraction function to both the horizontal and vertical components. This function provided the amplitude on the main harmonics of the centroid movement according to the following equation:

$$x(n) = \sum_{i=1}^N A_i * \cos\left(\frac{2\pi f_i n}{F_s} + \phi_i\right) \quad 1)$$

where A_i , f_i , and ϕ_i are the amplitude, frequency, and phase, respectively, of the i^{th} tone of a multiple tone signal with N tones and F_s is the sample rate in samples per second of the input waveform signal.

RESULT AND DISCUSSION

All the experimental investigations were carried out at 1500 rpm and full load condition, with an intake pressure fixed at 1300 mbar. The intake air and the cooling water temperatures were set at 308 K and 333 K, respectively. This regime was chosen near to the maximum torque regime for this engine in order to promote a knocking behavior, as well as the air to fuel ratio (AFR). It was measured at the exhaust with a linear lambda meter and it was maintained close to the stoichiometric value ($\lambda=1$) by adjusting injection duration.