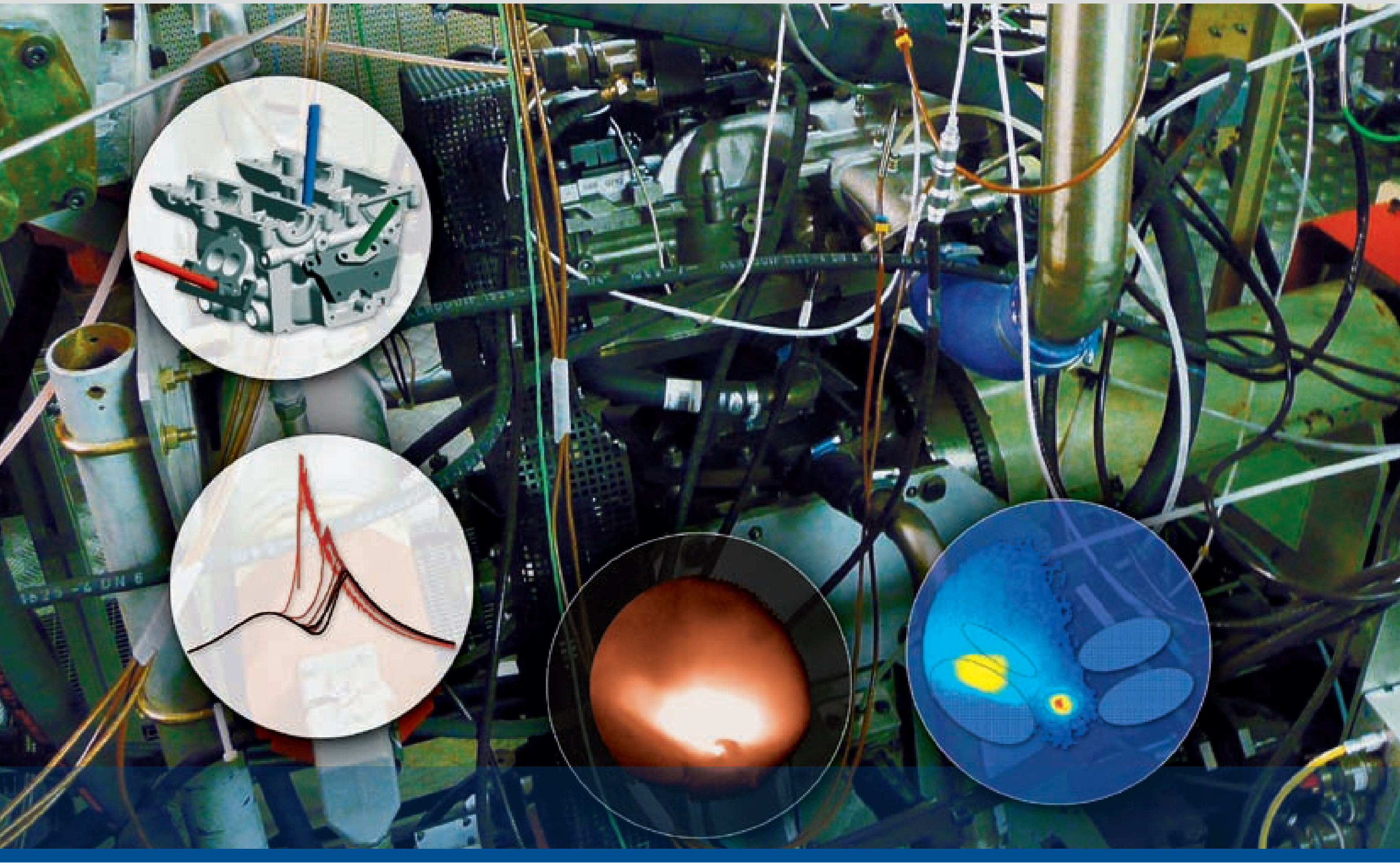

Pre-ignition in Highly Charged Spark Ignition Engines – Visualisation and Analysis

Highly boosted spark ignition engines must confront violent forms of pre-ignition limiting the maximal low-end torque. French research institute IFP presents here an innovative tool allowing a better understanding of this phenomenon and a structured reasoning considering all potential causes of this phenomenon. Advanced statistical analyses of the combustion process and direct visualisations inside the combustion chamber are successfully combined to accurately assess the development of pre-ignition. This coupled approach provides an efficient tool for analysis and development of new engines and new control concepts on IFP test beds.

1 Introduction

The massive introduction of downsized spark ignition engines for small and middle class vehicles will help satisfy CO_2 emissions targets decided by the European Union. These engines are designed and optimised to achieve very high loads but knocking is not the only limit that they have to face.

Stochastic and violent forms of pre-ignition have indeed occurred at low engine speeds and high charging pressures close to full load since the first developments of boosted gasoline engines. Even if this phenomenon bears some similarities with knocking, it can be so violent that a single occurrence may destroy the engine. Thus, a great challenge for European car manufacturers, suppliers and research institutes resides in identifying the mechanisms explaining this abnormal combustion to set back the maximal performance of future highly boosted spark ignition engines.

IFP has been working on this subject for a long time [1, 2]. Numerical investigations have indeed highlighted several times the complexity of this phenomenon and even if CFD simulations have proved to be useful in some cases they are still limited especially because of the stochastic aspect of pre-ignition.

It is thus necessary to adopt a structured and original approach based of course on a better understanding of the phenomenon but also on an accurate control of combustion at high load to detect each occurrence of pre-ignition. Visualisations and thermodynamic analyses can be successfully combined to follow the development of pre-ignition and to discuss its potential causes, **Figure 1**. At the same time, robust statistical tools must be developed to accurately detect all pre-ignitions and to efficiently cope with their violence.

2 Statistical Analysis

2.1 Stakes

Pre-ignition appears randomly and sporadically, it is thus necessary to record a lot of occurrences to analyse this phenomenon but on the other hand it is also unfortunately really risky because of its potential violence. Furthermore, a whole range of pre-ignitions releasing more or less energy exists [1] and it is quite difficult to distinguish a pre-ignition from normal combustions in certain cases, **Figure 2**. Particularly, a simple “on/off” criterion is not judicious to quantify the pre-ignition frequency since it is really complicated to define a limit within this whole panel going from smooth and slow pre-ignitions which look like normal combustions ignited at the spark plug to very harsh and fast pre-ignitions leading to extreme in-cylinder pressures.

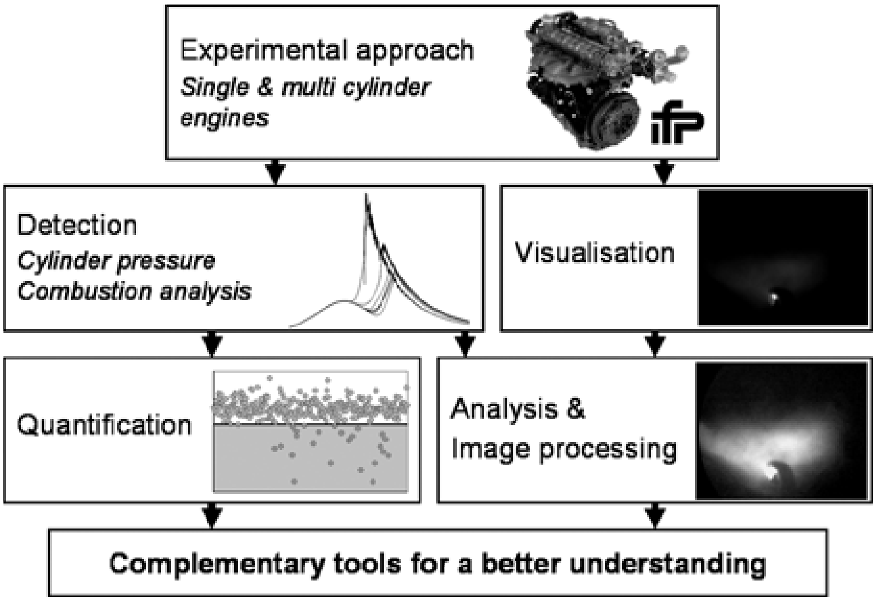

Figure 1: IFP approach for experimental investigations on pre-ignition

The Authors

Dipl.-Ing.
Jean-Marc Zaccardi
is working as a research engineer on gasoline engines at IFP in Rueil-Malmaison (France).

Dr.-Ing.
Matthieu Lecompte
is working as a research engineer on gasoline engines at IFP in Rueil-Malmaison (France).

Dr.-Ing.
Laurent Duval
is working as a research engineer and a project manager on signal and image processing at IFP in Rueil-Malmaison (France).

Dipl.-Ing.
Alexandre Pagot
is working as project leader on gasoline engines at IFP in Rueil-Malmaison (France).

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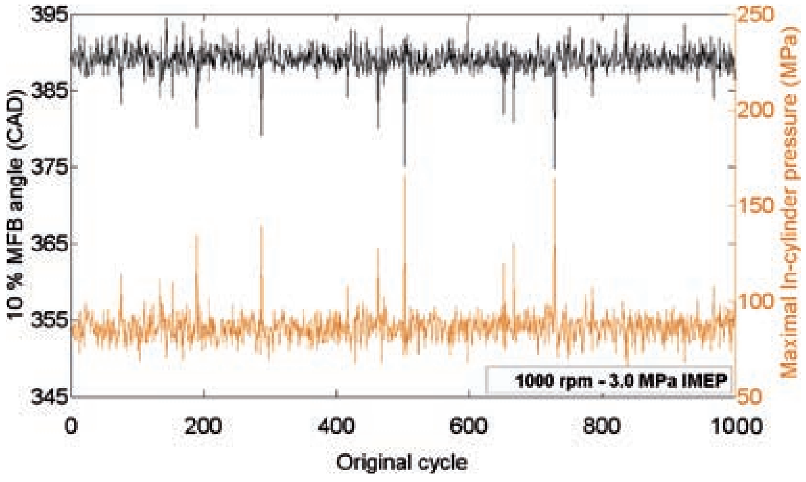

Figure 2: 10 % MFB angle and maximal in-cylinder pressure

This difficult quantification of pre-ignition occurrences makes really hard to establish the link between the technical definition of an engine and its sensitivity to pre-ignition. A statistical approach has thus been developed to tackle this problem and to define new reliable indexes and methodologies allowing the quantifications of the frequency and the intensity of pre-ignition. That way, it is not only possible to evaluate the impacts of an engine's settings and technical definition but also to avoid massive bulk auto-ignitions thanks to a precise quantification of all the intermediate pre-ignitions as soon as the combustion begins deviating.

Unfortunately, the widespread reference values used to quantify the combustion stability, such as the Coefficient Of Variation (COV) of IMEP, do not allow the quantification of every pre-ignition. Two reasons explain this lack of representativeness. First of all, the COV of IMEP is basically not the best indicator to characterize pre-ignitions. Indeed, it has been observed that some slow pre-ignitions may lead to the same IMEP as some normal combustions. Additionally, cycle-by-cycle IMEP depends on an interaction of several parameters throughout the whole combustion process (in-cylinder charge motion, air-fuel ratio distribution, ignition and injection characteristics, heat transfers). Thus, the characterisation of an engine's sensitivity to pre-ignition through a statistical analysis of IMEP may hide some phenomena since even a pre-ignition starting slowly a few crank angle degrees before the spark could obviously looks like a normal combustion and would not be necessarily detected through IMEP. In addition, a classical COV of IMEP or of maximal in-cylinder pressure for instance is coherent only if the mean value really represents the mean behaviour of the combustion. In other words, this mean value must be representative of each cycle and it can not be the case when pre-ignitions appear because these cycles really stand out from the crowd of normal combustions.

To compensate these shortcomings, the most logical and promising method consists in supervising the first crank angle degrees of combustion, i.e. the initiation phase, through a statistical analysis of 10 % Mass Fraction Burned (MFB) [1] or even 1 % MFB angles [3]. These indicators have the great advantage to be representative of the initiation phase timing which is the basic abnormal characteristic of pre-ignition.

2.2 Standard Statistics versus Robust Statistics

Besides, standard statistical estimators are not efficient when pre-ignitions appear; indeed, the main drawback of classical mean and standard deviation lie in their great sensitivity to outliers. A few outliers in a given data sample of 10 % MFB angles are sufficient to significantly affect its mean and standard deviation. Therefore, it is impossible to evaluate a reliable index representing the pre-ignition frequency based on these estimators. Robust statistical estimators like the median and the Median Absolute Deviation [4] should be used to overcome this sensitivity and to separate normal combustions from pre-ignitions, **Figure 3**.

The example shown in Figure 3 represents a large data sample with 1000 cycles. However, such a large quantity of data is of course not always available in practice. As a consequence, these new robust indicators were also calculated with only the first twenty cycles of the same recording, **Figure 4**. Results showed that they were almost insensitive to outliers even in the case of reduced a sample. The robust mean and the robust standard deviation have indeed roughly the same values whatever the data sample size is. This robustness is a considerable asset to accurately detect pre-ignitions cycle after cycle and is very encouraging regarding the transposition to an on-line detection tool.

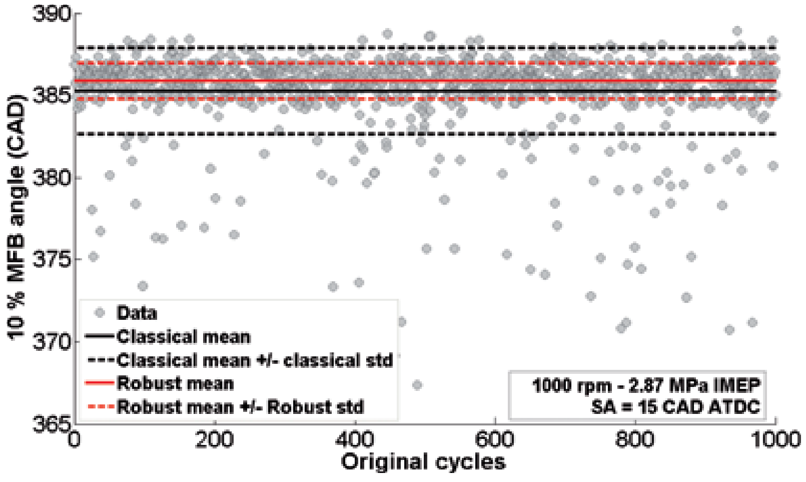

Figure 3: Comparison of classical and robust statistical indicators

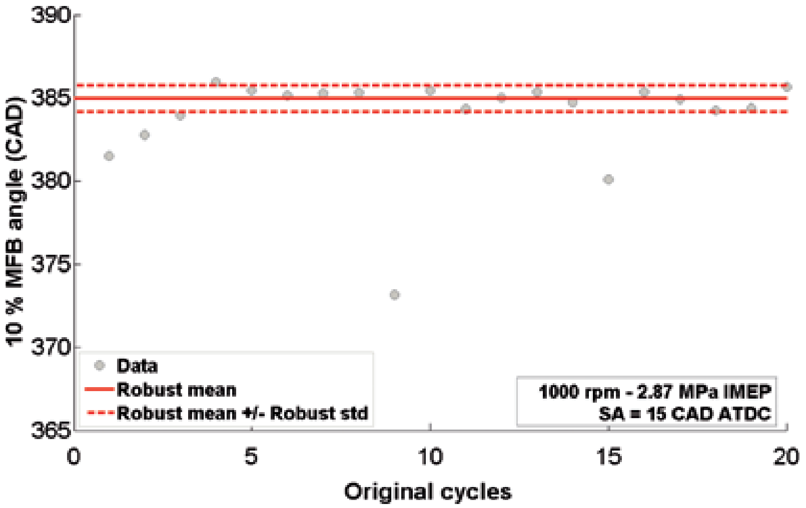

Figure 4: Calculation of robust using only the first twenty cycles of the recording presented in Figure 3

2.3 Modelling

A second method based on a statistical modelling of the 10 % MFB angle was developed in order to quantify the pre-ignition frequency. The hypothesis motivating this approach is that the dispersion of the 10 % MFB angles in the case of normal combustions follows a predetermined statistical distribution. This dispersion is generally explicitly or implicitly represented by a normal distribution. However, this well known symmetrical distribution is not always really adapted since the 10 % MFB angle depends on several parameters like for instance the EGR rate, the local air/fuel ratio at the spark plug and of course the in-cylinder charge motion.

In fact, the analyses of several data samples of 10 % MFB angles show that the real shape of this distribution usually has an asymmetrical aspect linked to the parameters listed above but also to the combustion timing which is always more or less shifted towards the expansion stroke. It explains that the 10 % MFB angles distributions are usually quite abrupt on the low values side since the ignition timing represents an absolute inferior value when the combustion is normally triggered by the spark while the high values side is generally more diffused since it corresponds to the few combustions that are initiated too slowly and with too much instability.

Additionally, pre-ignition occurrences modify the experimental distribution shape by widening the distribution tail on the low values side, **Figure 5**, upper right-hand corner. The direct modelling

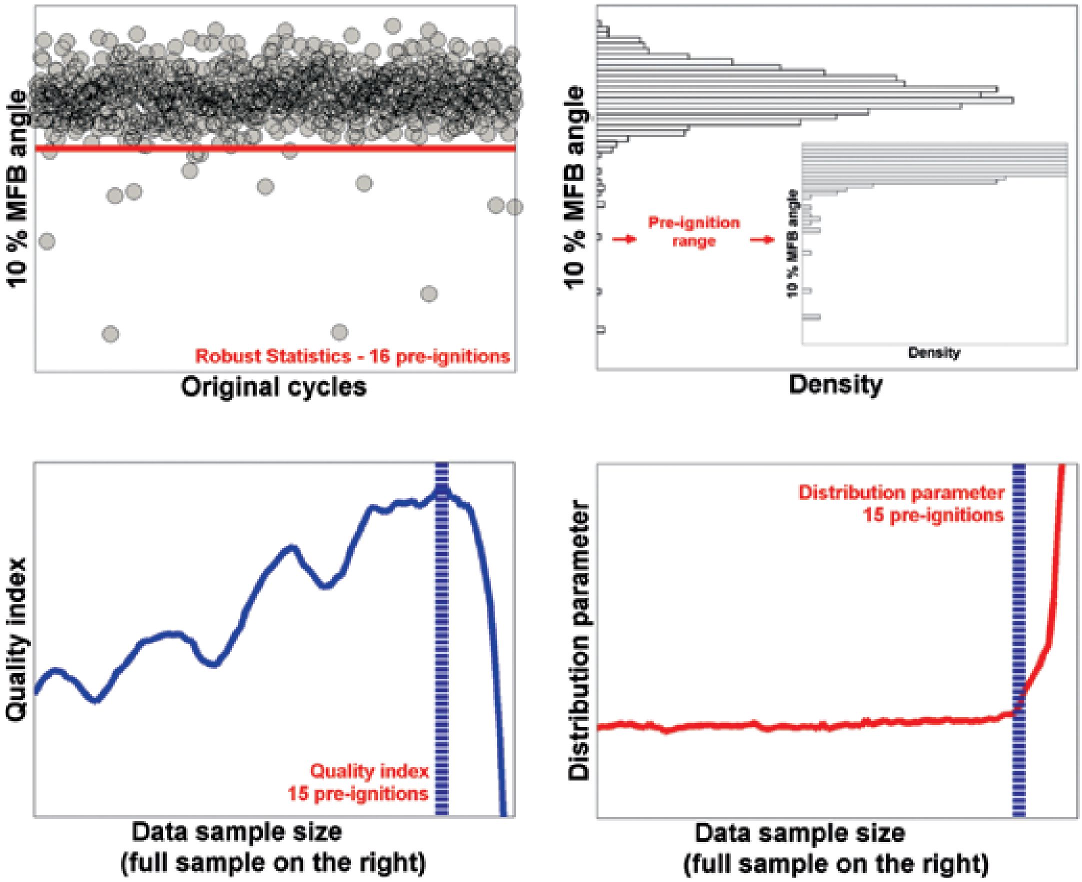

Figure 5: Identification of the pre-ignition frequency through a statistical process

Table: Main characteristics and settings of cameras

	Camera N°1	Camera N°2
Type	AVT Pike F100B	Phantom Miro 3
Resolution	1000*1000	800*600
Colour	B&W	Colour
Opening duration (CAD)	9	2
Acquisition per cycle	1	25

of this kind of data sample has no chance to be well representative of the experimental distribution since it is impossible to find a theoretical distribution that would take into account the asymmetrical aspect due to the slow combustions, and the asymmetrical aspect linked to pre-ignitions.

The quantification of the pre-ignition frequency and the correct modelling of normal combustions ask thus to set aside abnormal combustions. This sorting step can be done through an iterative and automatic process consisting in realizing successive statistical fittings removing at each step of this iterative process the cycle which has the lowest 10 % MFB angle and which is then potentially a pre-ignition.

The judicious choice of the theoretical probability distribution then allows to efficiently define the limit between normal combustions and pre-ignitions. Two approaches are conceivable either by defining a quality index of the successive modellings or by following the evolutions of the parameters defining the chosen probability distribution. In the first case, the pre-ignition frequency is determined by the numbers of cycles that must be removed from the original data sample to reach the maximal relative quality index, Figure 5, lower left-hand corner). In the second case, the pre-ignition frequency can be determined thanks to particular values of the parameters defining the chosen probability distribution. The progressive removal of cycles having the lowest 10 % MFB angles indeed unveils some particular values like maximal values or inflexion points only when all the pre-ignitions have been removed, Figure 5, lower right-hand corner. The particular value that has to be analysed depends on the choice of the parameters and also of course on the choice of the theoretical probability distribution (a non exhaustive list of distributions can be found in [5]).

The comparison of the results obtained with the first method based on robust statistics and with the second method based on the iterative modellings has always yield satisfactory results so far. These tools also have the basic advantage to consider that the underlying distribution is not symmetric. This main feature explains why they lead to an accurate quantification of pre-ignition and justifies their use when different engines or impacts of different settings on the same engine are to be compared. That is also why the first tool based on robust statistics has been associated to direct visualisations to extract more efficiently the relevant data regarding pre-ignition. Additionally, some other tools have also been developed at the same time to complete our analysis toolbox. Various methodologies have been defined concerning the exploitation of the links between different combustion indicators as well as the identification of combustion patterns that would show a possible determinism in pre-ignition phenomenon.

3 Direct Visualisations

3.1 Imaging System

Two CCD cameras were used in this work to visualise pre-ignition in the combustion chamber. Their characteristics are summarized in the **Table**.

The camera was connected to an air-cooled endoscope placed on the flywheel side of the cylinder head. To protect the endoscope, a specific sapphire window was inserted into the cylinder head. This window has been specifically developed for our application and allows the visualisations of a violent combustion ignited by a pre-ignition. The field of view obtained by our optical set up is given in **Figure 6**.

One objective of this direct visualisation is to determine the spatial origin of the pre-ignition. This information can help us discuss the potential causes of abnormal combustions. All visualisations and results presented here were obtained with a gasoline single cylinder engine operated at a speed of 1000 rpm at full load.

3.2 Methodology of Extraction

A pre-ignition phenomenon is a sporadic event and the beginning of this abnormal combustion can occur in a cycle

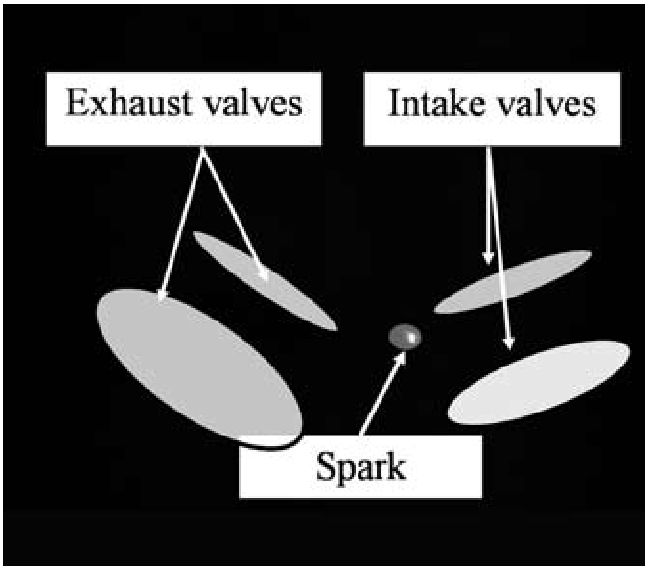

Figure 6: Field of view in the combustion chamber

around the top dead center or near to the spark advance (SA) timing. As there is at least one image per cycle and at least 300 cycles per acquisition, a quantity of images have been acquired for each experimental condition. So a specific methodology has been developed to extract the relevant information contents in our acquisitions, **Figure 7**.

As we have a lot of results with the camera N°1 and to simplify the presentation of our methodology, all images presented in this part come from camera N°1 (one image per cycle). Obviously, the methodology presented below is valid and useable whatever the type of camera. The additional information given by high speed camera will be discussed in a second time.

The first step of our treatment is to identify the abnormal combustion cycle. For that, the specific statistical tools developed by IFP and discussed before have been used. These new tools are necessary to select only the pre-ignition images, Figure 7/step 1.

Secondly, a link between pre-ignition images and combustion analysis of each cycle must be done. This is due to the fact that the beginning of pre-ignition can occur anytime but the camera is triggered at a constant timing. Moreover, the heat release may be different from one pre-ignition cycle to another. So for each image we associate the value of MFB at the end of camera exposure. This information gives us a criterion to select usable images. To highlight this aspect, we present for two different acquisitions, Figure 7/step 2, the camera opening duration in the cycle, the MFB during the cycle and the mean MFB calculated on 300 consecutive cycles. In the first case, the top one, a great part of the mixture was burning during the camera opening duration. This image is unusable for an accurate ignition location. We prefer images like the bottom one, where the end of camera exposure corresponds to the beginning of the combustion (MFB ~ 5 %).

Such images introduce the last step of our treatment specifically developed: image processing. Although the signal-to-noise ratio is relatively poor due to light coming from combustion only, our image processing method based on non-linear image denoising and enhancement based on the discrete wavelet transform [6] is very efficient in this condition. In this example, our processing allows us to visualise a chemically reacting area on the exhaust side of the combustion chamber, Figure 7/step 3.

4 Pre-ignition location

First of all, we analyse each extracted images and one very interesting result is the evolution of the location of the pre-ignition. Indeed, **Figure 8** shows two pre-ignitions obtained in the same experimental conditions (coolant and charge temperature injection, ignition…). On the left side, the ignition appear close to the intake valves and on the right side the pre-ignition begins on the exhaust side of the combustion chamber. In these two cases, the ignition begins at the same time and the MFB have the same shape. The combustion analysis cannot differentiate one case from another.

By the light of this example, it is relevant to know if there is a preferential zone of ignition for some given experimental conditions. The superposition of all images recorded at the beginning of the pre-ignition cycle informs us on the spatial origin of the pre-ignition as well as its repeatability. We present, **Figure 9**, the results obtained with the same single cylinder engine working with two experimental conditions. In these two cases, we use more than one hundred pre-ignition events for each map. In these results, the exhaust valves zone is the preferential area of ignition. However, the location in the two cases presented here exhibit sensitive differences. These first results are very encouraging because they pave the way to a comprehensive parametric study. These new qualitative results perfectly complete the quantitative information obtained by the statistical criterion.

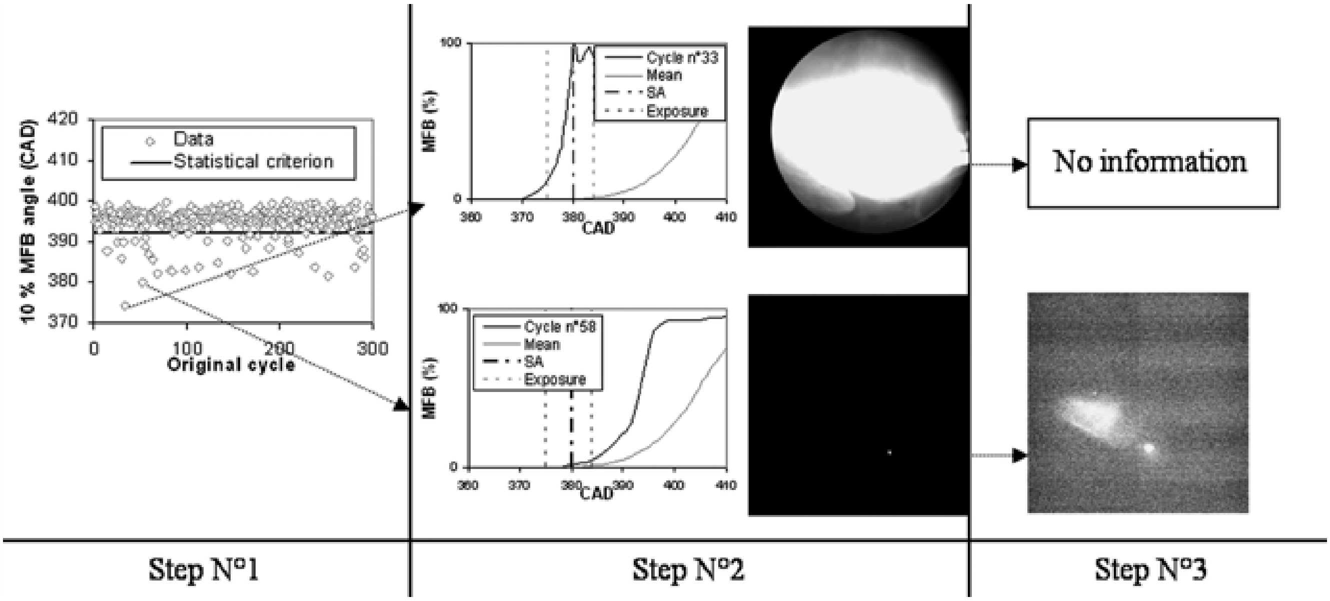

Figure 7: Extraction of the relevant images

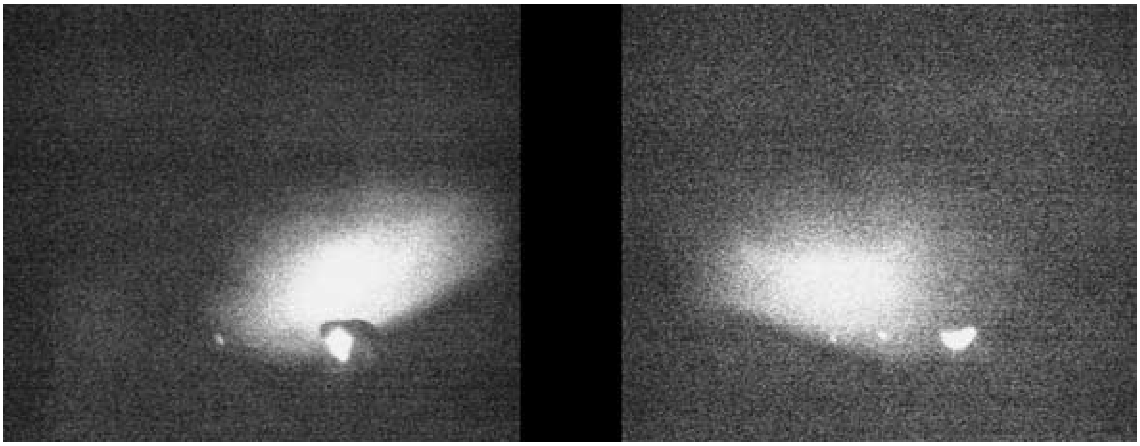

Figure 8: Examples of pre-ignition with different locations

However, we must be cautious at the time of the interpretation of this kind of image. Indeed, we are only able to interpret a three dimensional effect on two dimensions and in the Figure 8 a lot of images apparently outline a reaction zone behind the spark plug plan. Acquisition of images with another field of view could usefully complement the map of pre-ignition zone.

5 High Speed Camera Potential

Camera N°1 has been used with a long exposure time (9 CAD) for two main reasons:

- to obtain enough signal (depends on the camera sensitivity)
- to increase the potential to capture an abnormal combustion.

The net advantage of an high speed camera resides in gathering a lot of images in one cycle. It thus becomes easier to capture the beginning of a pre-ignition and to follow the whole combustion process. Using this kind of camera improves the productivity of results because there is at least one usable image for each pre-ignition cycle, Figure 7/step 2. We present on the **Figure 10** the mean rate of heat release ROHR on 300 cycles and the ROHR of a pre-ignition cycle (cycle N°250). This pre-ignition cycle is very fast and violent but with the camera N°2, we can split the ROHR and obtain a lot of interesting images. Despite the small exposure time (2 CAD), the signal is sufficient and we can precisely analyse the spatial origin and the propagation of this abnormal combustion.

Another information given by the camera N°2 is colour. Its analysis could be used to go further in the understanding of the pre-ignition phenomenon and will be probably studied in our future work.

6 Outlook

Several hypotheses have already been formulated to explain the potential causes of pre-ignition [7]. Nevertheless, the interaction between these different possible causes makes the analysis and the control really tough. Resultingly, pre-ig-

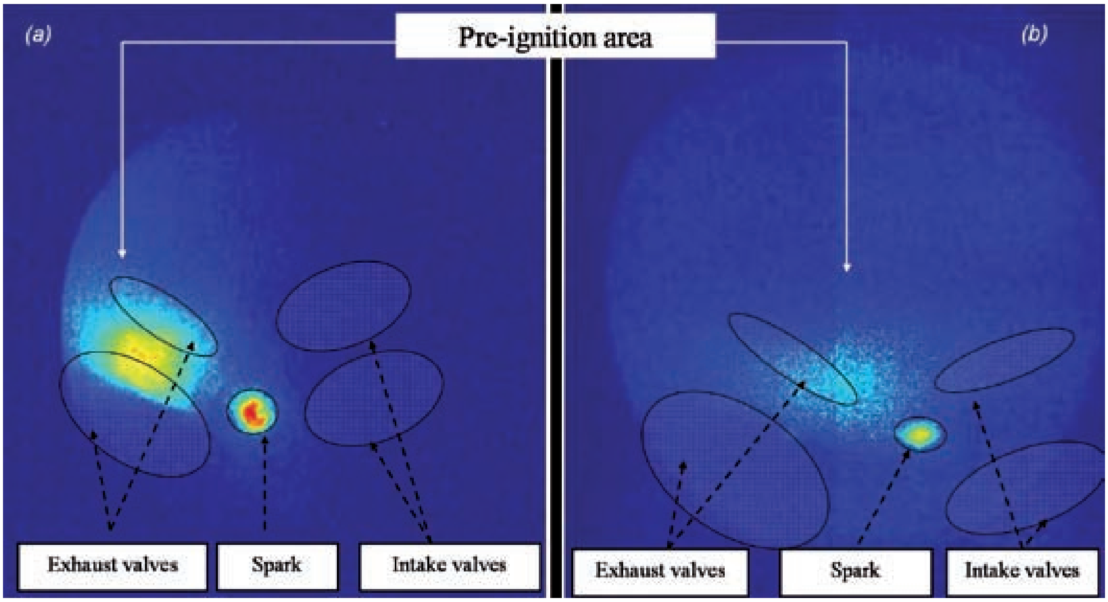

Figure 9: Pre-ignition zone – case a: sample of 101 images and case b: sample of 132 images

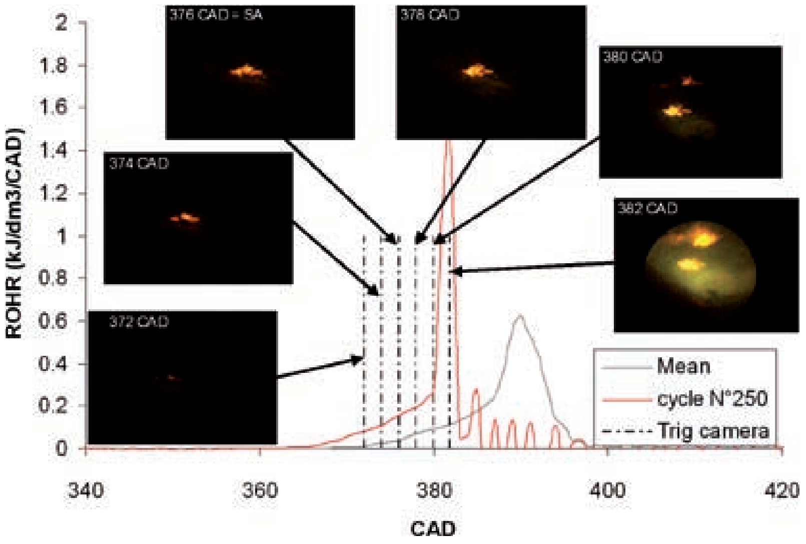

Figure 10: Continuous record of a pre-ignition event

nition remains a critical issue during the development on new highly boosted spark ignition engines.

Two innovative statistical approaches have been used to develop reliable indexes and methodologies, allowing a precise quantification of the pre-ignition frequency. It is now possible to compare different configurations and to guide the design of new engines on test bench. It is also conceivable to transpose some of these tools for online analyses either for steady state operations or for transients.

We prove the deep interest in combining statistical analysis and direct visualisation. Thanks to our experimental set up and methodology, we make up a map of preferential zone of pre-ignition and we show that these zones depend on the experimental conditions. Such maps could be improved with the high speed camera results.

References

[1] Vangraefschepe, F.; Zaccardi, J.-M.: "Analysis of destructive abnormal combustions appearing at high load and low engine speed on high performance gasoline engine", The Spark Ignition Engine of the Future, SIA Congress, 2007

[2] Zaccardi, J.-M.; Duval, L.; Pagot, A.: "Development of Specific Tools for Analysis and Quantification of Pre-ignition in a Boosted SI Engine", SAE Paper 2009-01-1795

[3] Manz, P.-W.; Daniel, M.; Jippa, K.-N.; Willand, J.: "Pre-ignition in highly-charged turbo-charged engines. Analysis procedure and results", 8. Internationales Symposium für Verbrennungsdiagnostik, Baden-Baden, 2008

[4] Huber, P. J.: "Robust Statistics", John Wiley and Sons, New-York, 1981

[5] Saporta G. : "Probabilités, analyse des données et statistique", Technip, 2006

[6] Chaux, C. ; Duval, L.; Benazza, A.; Benyahia, J.; Pesquet, J.: "A nonlinear Stein based estimator for multichannel image denoising", IEEE Transactions on Signal Processing 56, Nr. 8, S. 3855-3870, 2008

[7] Willand, J.; Daniel, M.; Montefrancesco, E.; Geringer, B.; Hofmann, P.; Kieberger, M.: „Grenzen des Downsizing bei Ottomotoren durch Vorentflammungen", MTZ Mai 2009