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Evaluation of the effects of a Twin Spark Ignition System on combustion stability of a high performance PFI engine

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Abstract

The continuous demand for high performances and low emissions engines leads the engine manufactures to set the operating range of combustion devices near to their stability limit. Combustion stability is closely related to the formation of the first ignition kernel: an effective way of lowering Cycle-by-Cycle Variation (CCV) is to enhance the start of combustion by means of multiple sparks. A Ducati engine was equipped with a Twin Spark ignition system and a consistent improvement in combustion stability arised for both part load and full load conditions.

At part load a sensible reduction of cycle-by-cycle variability of indicated mean effective pressure was found, while at full load condition the twin spark configuration showed an increase of power, but with higher knocking tendency. The aim of this work is to better understand the root causes of the increased level of knock and to make a critical evaluation of most used knock indexes, by means of an accurate analysis of the experimental and simulated pressure signals.

The numerical methodology based on a perturbation of the initial kernel by a statistical evaluation of mixture condition at ignition location. A lagrangian ignition model developed at University of Bologna was used, here modified to take into account the statistical distribution of mixture around the spark plugs. The RANS simulations proved to be accurate in representing all the main information related to combustion efficiency and knocking events.

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Keywords: High Performance Engine; Knock; Twin Spark; Cycle by Cycle Variability;

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Nomenclature

A/F	Air to Fuel Ratio
ADV	Spark Advance
CCV	Cycle by Cycle Variation
CHR_{NET}	Net Cumulative Heat Release
DKI	Dimensionless Knock Indicator
DNS	Direct Numerical Simulation
IMEP	Indicated Mean Effective Pressure
IVO	Intake Valve Opening
IVC	Inlet Valve Closing
LES	Large Eddy Simulation
MAPO	Maximum Amplitude of Pressure Oscillation
IMPG	Integral Modulus of Pressure Gradient
IMPO	Integral Modulus of Pressure Oscillation
MFB10	10% Mass Fraction Burned
MFB50	50% Mass Fraction Burned
MFB90	90% Mass Fraction Burned
MS	Mono Spark
PFI	Port Fuel Injection
RANS	Reynolds Averaged Navier-Stokes equations
SI	Spark Ignition
TS	Twin Spark

1. Introduction

The quest for high performances and low emissions leads engine manufactures to trim the operating range of combustion devices near their stability limit. The capability of accurately simulate the engine in such a critical conditions is indispensable and many steps are made, both in terms of CFD modeling and computational hardware development.

There are above all two limits that restrict engine operation because of CCV: in the lower part-load range one should mention the misfiring limit, which comes into play primarily in the course of high degrees of charge dilution (residual gas, air) and the associated increase in cyclic fluctuations. At full load, on the other hand, the knock limit restricts optimum-efficiency combustion control.

One effective way to improve combustion stability at low load condition is the use of Twin Spark ignition system: Bozza et al. [1] developed a quasi dimensional three-zone model for the geometrical evaluation of the double kernel formation, and applied it for the simulation of an High-EGR VVT-Engine, in both mono spark and twin spark configuration.

Cavina et al. [2] showed how a multiple discharge is an effective way of improving ignitability of lean and diluted mixtures, shortening ignition delay and combustion duration, and preventing misfire occurrence without any impact on the intake fluid dynamics, and proposed a methodology for real time control purpose.

Modeling the CCV (Cycle by Cycle Variation) of spark ignition engine is essentially based on a forced perturbation of the combustion evolution in the chamber: a lot of methodologies today available in literature are based on this mechanism, but the key issue is the way these perturbations are selected. The imposition of a change in the combustion evolution must be based on real engine condition to be predictive.

Even a simple model for cyclic variation based on a Monte Carlo approach [3] can correctly represent the engine behaviour, but no practical information can be used for engine design.

Table 1. Engine configuration

Bore	106mm
Stroke	67.9mm
Regime	8500 rpm
Load	Full load
Engine ignition system	Mono Spark / Twin Spark
Spark Advance	Sweep until max IMEP
λ	0.83

The actual feasible way to effectively reproduce CCV is by performing full 3D CFD LES (Larg Eddy Simulation) of the engine. Tatschl et al. [4] and Vitek et al. [5] investigated the root causes of CCV by means of a combined 1D-3D simulation: the in-cylinder analysis was based on LES approach. They concluded that the instantaneous flow field of individual cycles in different cross-sections of the cylinder demonstrated a combined small- and large-scale nature of the flow field fluctuation, which interacts closely with the spray droplet distribution and fuel vapor concentration.

In the present work the authors propose a RANS (Reynold's Averaged Navier-Stokes equations) methodology for the evaluation of combustion instabilities based on mixture composition at the spark plug. In a previous work [6], the authors investigated the root causes of the cycle-by-cycle variability increase with leaner combustion, by means of a joint numerical and experimental approach: the authors showed that the combustion sensitivity to the initial perturbation of the mixture air index at spark location and to the level of in-cylinder air index homogeneity increases, due to the lower laminar combustion speed of leaner mixtures. The authors concluded that efficient mixing processes are mandatory any time the engine operates with suboptimal air indexes (far from those giving the maximum laminar speed).

The aim of this work is the evaluation of combustion behaviour of a Ducati high performance engine, equipped with a twin spark ignition system. The low stroke to bore ratio makes the combustion very critical in the narrow volume of the combustion chamber, especially under part load condition. In this configuration the twin spark ignition greatly improves the stability of the engine, but also in full load condition the fastest initial kernel development reduced the variability of the engine. The engine was analyzed by the authors in previous works [7] [8]: the actual contribution is a critical evaluation of the results, by deepening the correlation between knock events and pressure signal.

Due to confidential agreement with Ducati some of the data in the present paper will be referred to a conventional condition.

2. Experimental analysis of combustion efficiency and knock

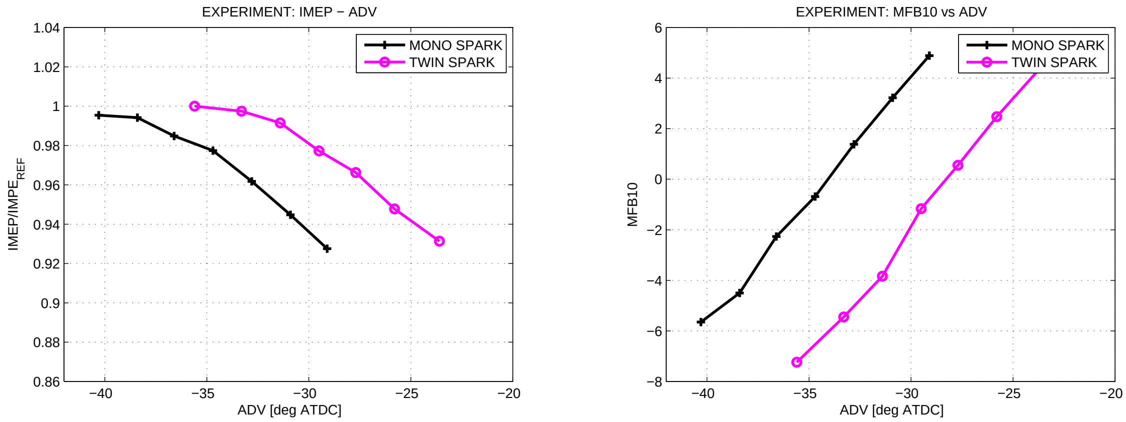
The engine under analysis is a Ducati high performance engine, here evaluated in the configurations of Tab. 1

The engine run on the test bench equipped with a pressure sensor located in the chamber. The pressure traces of 300 engine cycles are recorded for each engine point analyzed for both the Twin Spark and Mono Spark configurations. The spark advance swept is accomplished by advancing the combustion until the maximum brake torque. The indicating parameters are extracted by filtering the pressure signal with a butterworth zero-delay low pass filter at 3kHz for IMEP and CHR_{net}, with a butterworth band-pass filter at between 5kHz and 20kHz for the high frequency parameters.

Fig. 1(a) summarizes the results found in previous works [7] [8], showing how the twin spark allows more efficient combustions, with higher values of maximum IMEP and faster combustions: the ADV of maximum brake torque is four degrees lower than the single spark configuration.

The increase in combustion rate is focused in the early stages (Fig. 1(b)), with a MFB10 (10% Mass Fraction Burnes) of twin spark configuration four degrees lower. This is the consequence of the double flame fronts initiated in the chamber. In order to better understand the relation between the combustion efficiency and combustion phasing an alternative approach needs to be implemented. In a previous work the authors [9] showed how the main combustion characteristics can be summarized by means of:

- Combustion initiation (MFB10-ADV)



(a)

(b)

Fig. 1. Spark advance sweep: (a) Imep swept - spark advance; (b) - Spark advance

- Combustion shape (Maximum value of ROHR)
- Combustion duration (MFB90-MFB10)

Corti et al [10] [11] showed that, within a specific engine configuration, all these parameters can be considered dependent on a single combustion information: the MFB50. The 50% of mass fraction burned represents the combustion phasing of the engine and an optimal value for full load condition is between eight and ten degrees after top dead center of combustion. In Fig. 2 the maps of IMEP for both TS and MS configuration are plotted against MFB50. The double ignition allows a better indicating efficiency, thanks to lower compression work caused by the faster initial combustion.

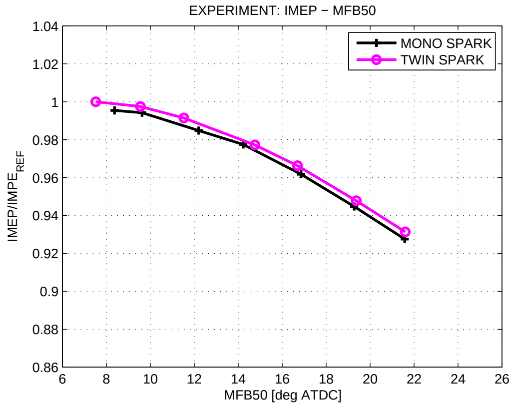


Fig. 2. Indicated Mean Effective Pressure versus MFB50

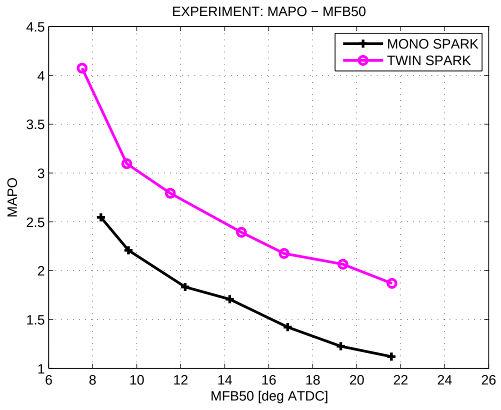


Fig. 3. Maximum Amplitude of Pressure Oscillations with respect to MFB50

The evaluation of knock is accomplished by means the analysis of MAPO, defined as Eq. 1

$$MAPO = max\left(|p|_{\theta_0}^{\theta_0+\zeta}\right) \tag{1}$$

where θ_0 is top death center of combustion and ζ is 70 degrees.

The knock tendency of the engine is depicted in Fig. 3, in which the mean value of MAPO of 300 cycles is plotted against combustion pahsing MFB50.

TS configuration reveals higher knock sensitivity on the whole range of spark advance sweept analyzed: an ADV control set for the same risk of damage would completely cancel the positive effects of better combustion efficiency. In order to gain a more deep insight in the origin of the higher pressure oscillation of the twin spark ignition a CFD analysis of combustion process is developed.

3. Description of the CFD RANS Simulation Methodology

The aim of the CFD simulation is the evaluation of combustion of Twin/Mono Spark engine and the understanding of the origin of the higher knocking behaviour of TS configuration. The flow chart of the methodology is sketched in Fig. 4. The first step is an accurate reconstruction of the mixture composition in the chamber. To this purpose a multi-step methodology [12] has been accomplished in FIREv2011 (AVL), and all the physics involved in the injection process are evaluated and validated.

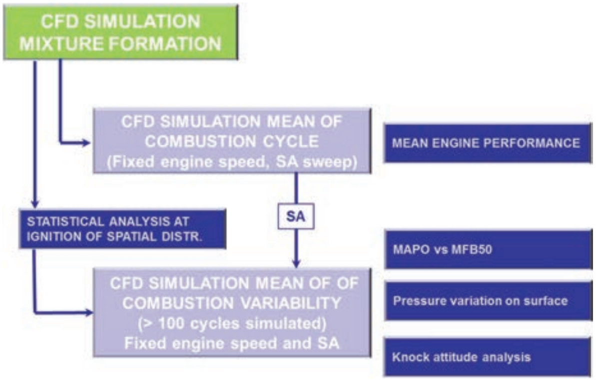


Fig. 4. Flow chart of the CFD methodology

Fig. 5 shows the equivalence ratio in the chamber at IVC and the location of the two spark plugs. The stars in the figures illustrate the spark locations: in the engine analyzed one spark is at the center of the chamber (the only one active in MS configuration), the other between inlet and exhaust valves. The fuel distribution is not homogeneous and the second plug is inside a leaner zone.

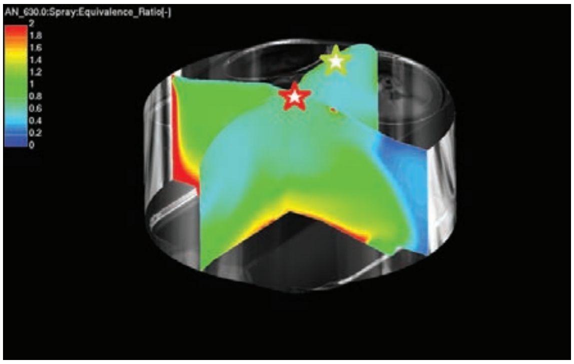


Fig. 5. Distribution of the fuel in the chamber at IVC

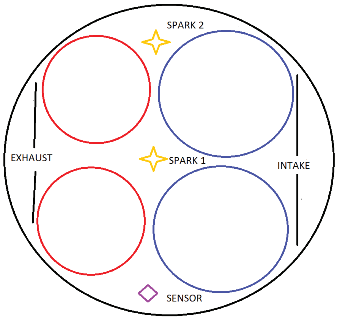


Fig. 6. Spark plugs and sensor position

The results of injection simulations are then mapped on a modified version of KIVA3D-code, developped at the university of Bologna. The main models implemented in the code are deeply described in [13] and listed in Tab. 2

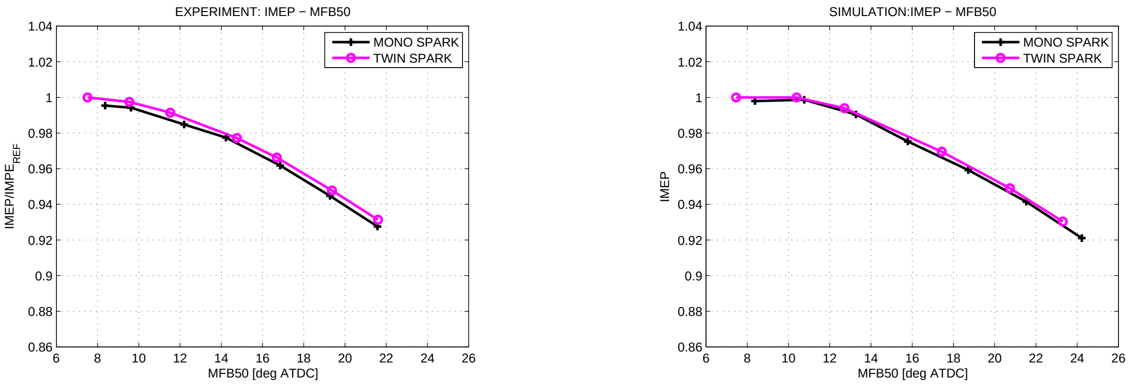
Table 2. KIVA3D CFD MODELS

Combustion	Extended Coherent Flamelet
Knock	two step autoignition model based on [14]
Ignition	Lagrangian ignition model [15] [16]

4. Simulation of combustion

The flamelet combustion model is tuned to correctly represent the real mean behaviour of the monospark configuration. Because of the cycle by cycle variability of the SI engines all the pressure traces of the experimental data are widely scattered, representing very different combustion characteristics. As it was shown in [17], the identification of the representative cycles is a key issue: the standard synchronous pressure average on a crank angle basis can lead to mean engine cycles which do not really exist. As it was shown in [8], the simulated mean cycle is compared witha selection of mean representative cycles, with MFB50 equal to the experimental mid-values.

The overall behaviour on the whole spark advance swept is in Fig. 7(a) Fig. 7(b): the simulation is able to represent both the combustion phasing of various spark advance (MFB50 on x-axis) and the higher efficiency of TS solution.



(a)

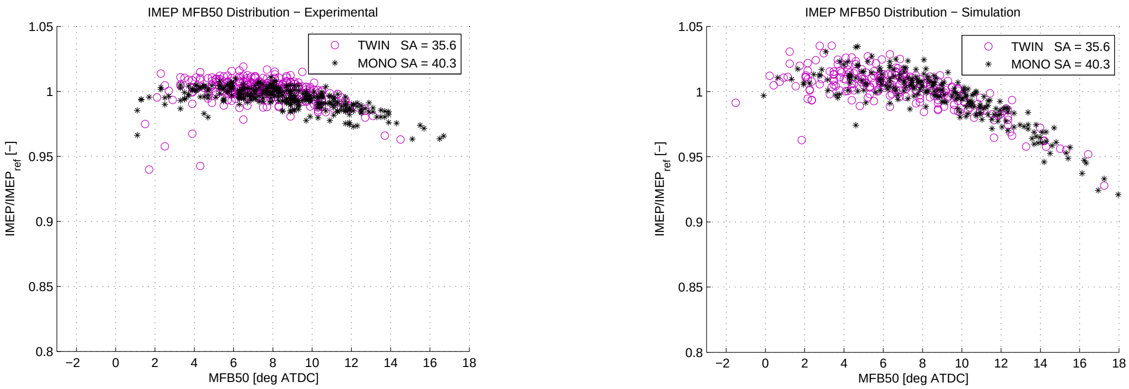
(b)

Fig. 7. Indicated mean effective pressure: (a) Experimental; (b) Simulated

The knocking combustion is a highly stochastic phenomenon and the criteria for the identification of thresholds is often based on statistics. The needs to better identify the behaviour of the to spark installations has taken the authors to implement a methodology for the evaluation of cycle by cycle variability. An effective way to simulate the cycle by cycle variation of a spark ignition engine is based on a forced perturbation of the combustion evolution, with particular emphasis on the early kernel development. The methodology of perturbation used ([7] [8]) is focused not only on a simple relationship between the perturbation strength and the amplitude of results, but it is grounded on the spatial characterization of the mixture and turbulence located at the spark plug.

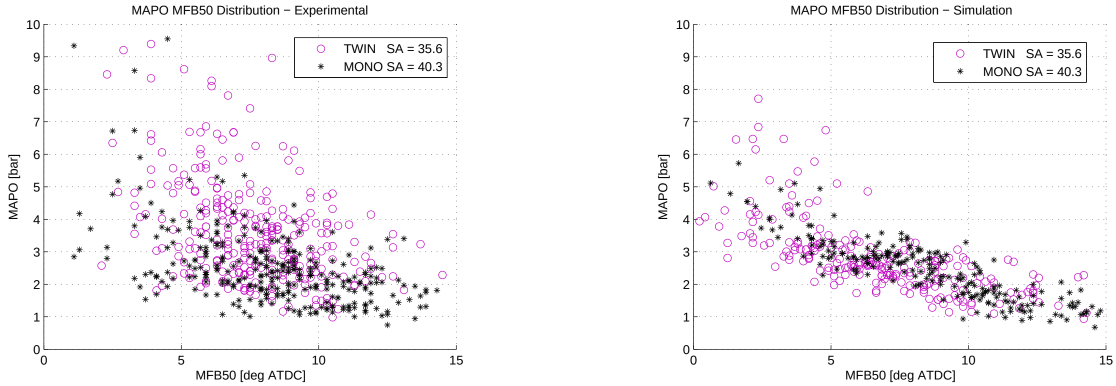
Fig. 8(a) and Fig. 8(b) show the comparison between the TS and MS configuration for both experimental and simulated results. The typical distribution of parabola-like patterns is well gathered, together with the higher tendency of TS configuration to have variability of IMEP.

The knock sensitivity can be extracted from Fig. 9(a) and Fig. 9(b): TS configuration has higher value of MAPO, expecialy in the lower MFB50.



(a) (b)

Fig. 8. Distribution of IMEP-MFB50: (a) Experimental; (b) Simulated



(a) (b)

Fig. 9. Distribution of IMEP-MFB50: (a) Experimental; (b) Simulated

5. Analysis of numerical results

The higher knock tendency revealed by the MAPO distribution of the TS configuration would nullify the advantage of faster combustions and better efficiency. The numerical simulations allowed to better characterize the phenomenom in terms of three dimensional spatial identification of pressure waves evolution. The constraints of the engine forced the installation of the sensor in the opposite position with respect to the secondary spark plug (Fig. 6).

MAPO knock index [17] is position sensitive: the index distribution at spark plug location is analyzed and depicted in Fig. 10. MS configuration showed higher level of MAPO all over the MFB50 distribution. The variability of MAPO with respect to sensor position not only doesn't allow defining absolute thresholds, but can condition the choice of the best configuration in a fictitious way. The amount of mass burned in autoignition condition during knock can be used as a robust tool to numerically identify the risk of damage. Fig. 11 shows that the MS configuration has an higher knock tendency than TS with the same combustion phase (i.e. MFB50).

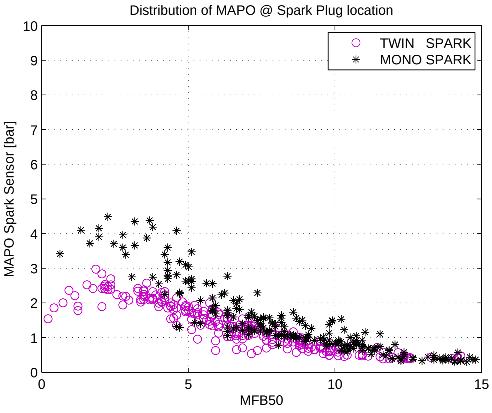


Fig. 10. MAPO at spark plug versus MFB50

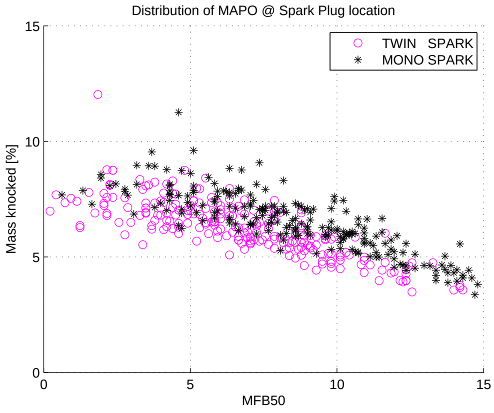
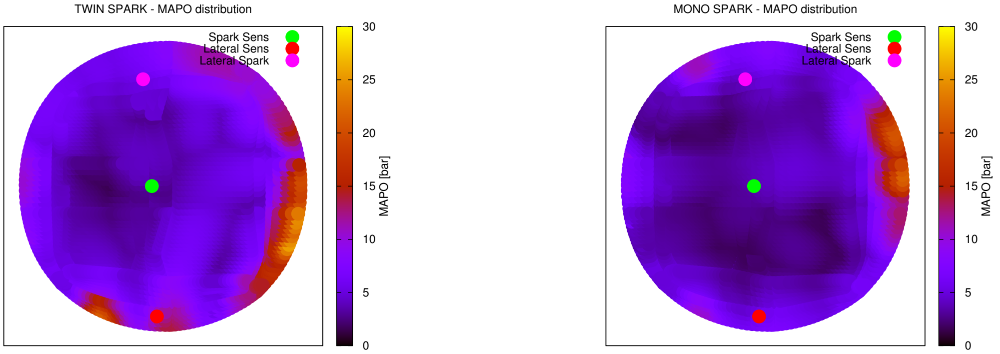


Fig. 11. Distribution of Mass Knocked with respect to MFB50

The distribution of pressure wave all over the combustion chamber is summarized in Fig. 12(a) and Fig. 12(b), where is plotted the distribution of MAPO on piston surface for the most severe cases of both MS and TS configuration. It is noteworthy the spatial variation of MAPO with a fixed knock event. The TS configuration has higher MAPO values near the side sensor location, but the most severe locations are in the intake squish for both MS and TS. The central spark location is characterized by low MAPO level.



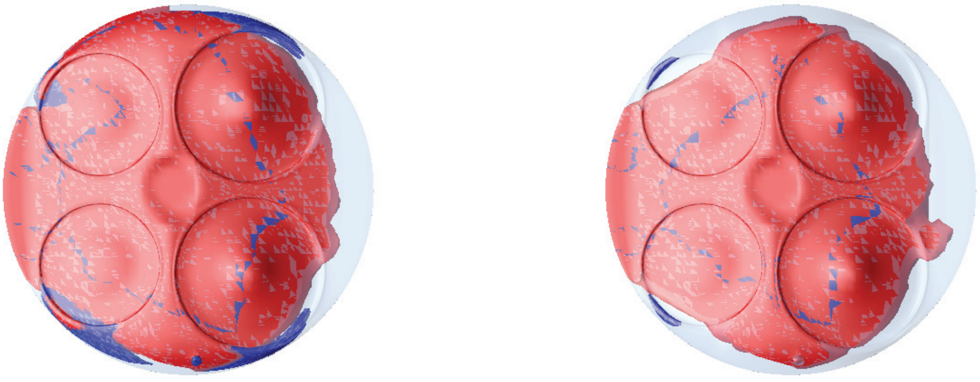
(a)

(b)

Fig. 12. Piston map of MAPO values: (a) Twin Spark configuration; (b) Mono Spark configuration

Fig. 13(a) and Fig. 13(b) show the evolution of the flame front and the formation of knocking volume (blue color). The MS location of knock are in the exhaust side, while in the TS condtion a big part of knocked mass is near the sensor plug location. The evolution of combustion of the TS configuration is not axis-simmetric, thus leaving the sensor zone as the late fresh mixture combustion location, here increasing the probability of knock.

It is interesting to analyzed the frequency content of the pressure traces at central and side locations for both MS and TS. Fig. 15(a) and Fig. 15(b) show the FFT of the pressure signal at central spark plug location, and it is clear the excitation of the radial resonance frequency of the chamber (i.e. 10500Hz). The MS configuration has an higher level of amplitude content because of the more simmetrical excitation of knocking events, thus justifying the higher



(a) (b)

Fig. 13. Flame front evolution: (a) Twin Spark configuration; (b) Mono Spark configuration

value of MAPO at central spark location. The tangential modes are not here intercepted because the center location is a nodal point of resonance.

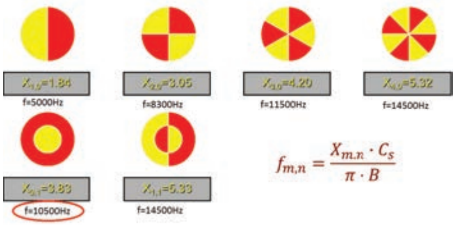
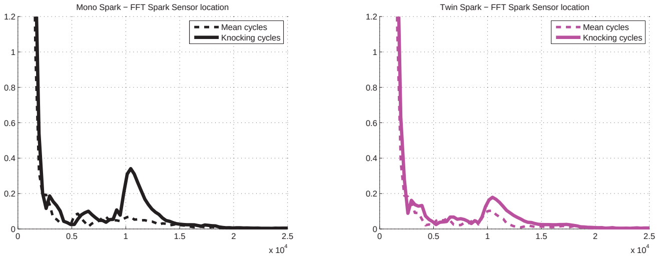


Fig. 14. Resonance frequency of the combustion chamber



(a) (b)

Fig. 15. Fourier Fast Transform of pressure signal at Spark location: (a) Mono Spark ; (b) Twin Spark

Fig. 17(a) and Fig. 17(b), show the FFT at side sensor location: in this case the tangential resonance frequancy are excited by knock events. The TS configuration has an higher level of the first resonance frequency because of the not simmetric evolution of the combustion.

6. Conclusion

A Ducati high performance engine equipped with a Twin Spark ignition system was evaluated at full load condition. The experimental analysis of pressure traces revealed a combustion efficiency improvement of the TS configuration, but an higher level of knock MAPO indexes.

A numerical methodology for the analysis of combustion and knock on a cycle by cycle basis is implemented and a more deep insight in the abnormal combustion is accomplished.The TS configuration showed higher level of MAPO at side sensor location, but the condition reversed when using the central spark plug sensor. The analysis of the pressure

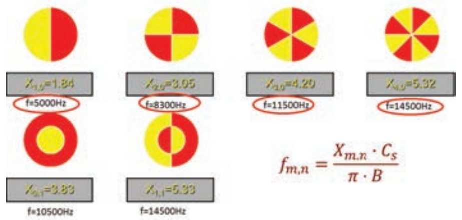
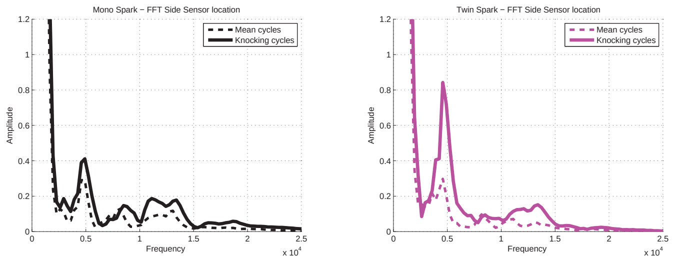


Fig. 16. Resonance frequency of the combustion chamber



(a) (b)

Fig. 17. Fourier Fast Trasnform of pressure signal at side sensor location: (a) Mono Spark ; (b) Twin Spark

traces all over the combustion chamber allowed defining the main characteristics of knocking of the engine. The TS combustion evolution was found not axis-symmetric, thus the autoignition zone activated primarly the tangential natural frequencies of the chamber then the radial ones. The MS configuration had a similar level of knocking risk if measured by means of total amount of mass burned in autoignition condition. The numerical methodology proved to be an usefull tool in the interpretation of engine behavior, and can be considered a start of point for the definition of knock indexes not sensible to specific installations and based on damage risk.

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