Chapter 5

Remote Combustion Sensing in Diesel Engine via Vibration Measurements

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Additional information is available at the end of the chapter

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Abstract

An efficient control of the combustion process is required in order to comply with regulations on pollutant emissions from internal combustion engines. Literature presents investigations devoted to explore the potentiality of externally mounted sensor (speed sensor, microphone, and accelerometer) for combustion diagnosis. A relationship exists between the combustion event measured via an in-cylinder pressure transducer and engine block vibration measured via an accelerometer. Time and frequency domain processing of acquired signals highlighted the correlation between parameters able to characterize the combustion development and features derived from the engine block vibration data. A methodology was developed by the authors that demonstrated to be suitable for real-time estimation of combustion progress based on engine vibration. A two-cylinder common rail diesel engine of small displacement was tested; two configurations were investigated, naturally aspirated, and turbocharged. The in-cylinder pressure and block vibration signals were acquired and processed in time and frequency domains. The vibrational components mainly related to the combustion process were extracted, and indicators of the combustion positioning were computed. The angular positions of start of combustion (SOC) and MFB50 computed via the heat release curve by means of the in-cylinder pressure measurements were compared to those obtained by means of the accelerometer signal. High correlation coefficients were obtained for the data acquired during the testing of both naturally aspirated and turbocharged configurations in the complete engine operative field.

Keywords: diesel engine, combustion, in-cylinder pressure, engine vibration, non-intrusive measurements

1. Introduction

Future regulations on internal combustion engine will require continuous tightening of pollutant emissions from internal combustion engines. Literature highlights considerable research activity on combustion monitoring and closed-loop control systems in order to ensure improvement of exhaust and noise emissions and reduction of fuel consumption.

Due to the strong dependence of combustion characteristics (ignition delay, pressure rise rate, peak pressure, and combustion duration) from injection settings, algorithms for closed-loop combustion control via injection parameters have been developed [1–3]. In these algorithms, the target values are mapped versus load, speed, and other factors in order to optimize emissions/performance despite changes in fuel properties and engine aging.

Even if low-cost transducers for in-cylinder pressure measurements have been recently proposed, limitations related to reliability, lifetime caused by the harsh environment, and mounting problems still represent limiting factors for their employment.

Advanced methodologies have been proposed in which nonintrusive measurements are used to evaluate quantities able to provide information about combustion progress. These measurements offer the advantages of guaranteeing the absence of any type of interaction with the engine operation. Moreover, the sensors can be installed in any type of engine without the need of modification.

Among them, the most promising approaches are based on engine speed fluctuation, noise radiation, and vibration measurements. Crankshaft angular speed, noise emission, and vibration measurement methods have been proposed to be used during development and calibration stages of the engine and for onboard application to control the combustion progress.

The fluctuating waveform of crankshaft angular speed versus angle is caused by the imbalance between combustion torque and external torque. Engine speed frequency component signal has demonstrated to be correlated with the torque signal. Several methods have been proposed to extract from the crankshaft angular speed measurement information about the combustion progress. Ponti et al. [4] estimated the position where 50% of mass is burnt inside the cylinder starting from the instantaneous engine speed fluctuation analysis. Moro et al. [5] presented a method for in-cylinder pressure reconstruction based on engine speed signals. Taglialatela et al. [6] proposed a model to estimate the combustion quality by means of the processing of crankshaft speed signals. Desbazeille et al. [7] developed a methodology for combustion diagnosis via the angular speed variations.

Methodologies have been proposed for combustion monitoring via engine noise radiation. Microphones offer the advantages to be installed at a distance from the engine. Noise emission from internal combustion engines is a very complex signal whose quality and levels are strongly reliant on the engine type and architecture. Even if the microphone signal has demonstrated to be correlated with the combustion process, it is highly contaminated by noise components caused by many overlapping sources (injection, piston slap, valves, oil pump, and turbocharger). The complex processing, required to insulate the combustion-related component from the measurements, has resulted a limited research activity on this topic. Jiang et al. [8] presented a method for diesel combustion monitoring based on acoustic measurements. Chiatti et al. [9] developed a methodology to characterize the in-cylinder pressure development by means of the engine noise emission. Gu et al. [10, 11] used acoustic measurements for condition monitoring of diesel engines. Torii [12] presented a technique to separate the engine noise radiation into the contributions of combustion and mechanical noise. Kaul et al. [13] investigated the acoustic emissions response caused by various engine cycle events.

The rapid pressure change in the cylinder during the combustion process gives rise to the engine structure vibrations. Piston slap, valves impacts, and gear transmissions are unwanted vibration sources that are responsible for components that decrease the signal-to-noise ratio. Vibration-based algorithms have been developed and proposed for indirect investigation of combustion process. Polonowski et al. [14] analyzed the signals from accelerometers positioned in multiple placements and orientations on an engine with the aim of investigating the potential of these sensors for combustion characterization. Lee et al. [15] investigated the correlation between the maximum heat release rate and the engine vibration. Jia et al. [16] proposed a neural network to correlate the engine block acceleration and the heat release rate. Jung et al. [17] performed a closed-loop control for the combustion process based on the engine vibration signals.

A methodology was developed by the authors, in which the block vibration signal from two different configurations of a two-cylinder common rail diesel engine is processed for combustion positioning within the engine cycle. The configurations were naturally aspirated and turbocharged.

These are the main steps of the methodology:

- selection of the optimal positioning for the accelerometer;
- time frequency analysis of the in-cylinder pressure and vibration signals and evaluation of their coherence function in order to select a frequency bandwidth in which spectral components of in-cylinder pressure and engine block vibration exhibit strong correlation;
- processing of the accelerometer traces to extract the vibration components mainly related to the combustion process;
- computation of indicators for combustion evolution characterization via vibration signal [start of combustion (SOC), angular position, where the 50% of mass is burnt inside the cylinder].

Results obtained in the engines complete operative ranges proved that the methodology based on vibration measurement is suitable for the real-time estimation of combustion progress.

2. Experimental setup and tests

Measurements were carried out on a two-cylinder diesel engine equipped with a common rail injection system, whose main application is in micro cars and urban vehicles (its technical data are reported in **Table 1**).

Cylinders	2
Displacement	440 cm^3
Bore	68 mm
Stroke	60.6 mm
Compression ratio	20:1
Maximum power	8.5 kW @ 4400 rpm
Maximum torque	23 Nm @ 2400 rpm

Table 1. Engine specifications.

Two configurations of the engine have been tested: naturally aspirated and turbocharged.

The engine was installed with an asynchronous motor (Siemens 1PH7, characterized by nominal torque 360 Nm and power 70 kW) in the test bed of Engineering Department at Roma Tre University. The engine was managed by a fully opened ECU, in order to control injection parameters (injection strategy, injection timing, and duration).

HBM T12 was used for torque measurement. AVL Fuel Balance 733 was used for fuel consumption measurement.

The in-cylinder pressure was measured with a piezoelectric transducer AVL GU13P (the preheating plug was substituted by the pressure probe).

The engine speed and the crank angle position were measured by the optical encoder AVL 364C. It generates transistor-transistor logic (TTL) rectangular pulse signals: one is the trigger signal that was used to compute the engine speed; the other is the code division multiplexing (CDM) signal that was set to a resolution of 0.1 crank angle degrees.

An Endevco 7240C accelerometer was used to measure the engine block vibration. It is a high-temperature piezoelectric mono-axial accelerometer with a nominal sensitivity of 3 pC/g and a resonance frequency of 90 kHz. The vibration signal was conditioned via B&K Nexus device (amplifier and low-pass filter). A preliminary investigation was devoted to select the optimal position and orientation of the accelerometer, able to guarantee high sensitivity as regards the combustion event and low sensitivity to mechanical sources. Details may be found in Ref. [18]. The accelerometer was mounted on the top of the engine block by means of a threaded pin on one of the stud that fastens the cylinder head to the block. The mounting was chosen in order to ensure a rigid connection to the structural engine members.

Figure 1 shows the engine setup and a detail of the accelerometer location.

The sampling frequency was varied according to the engine speed, thus to ensure a fixed crank angle resolution of the signals.

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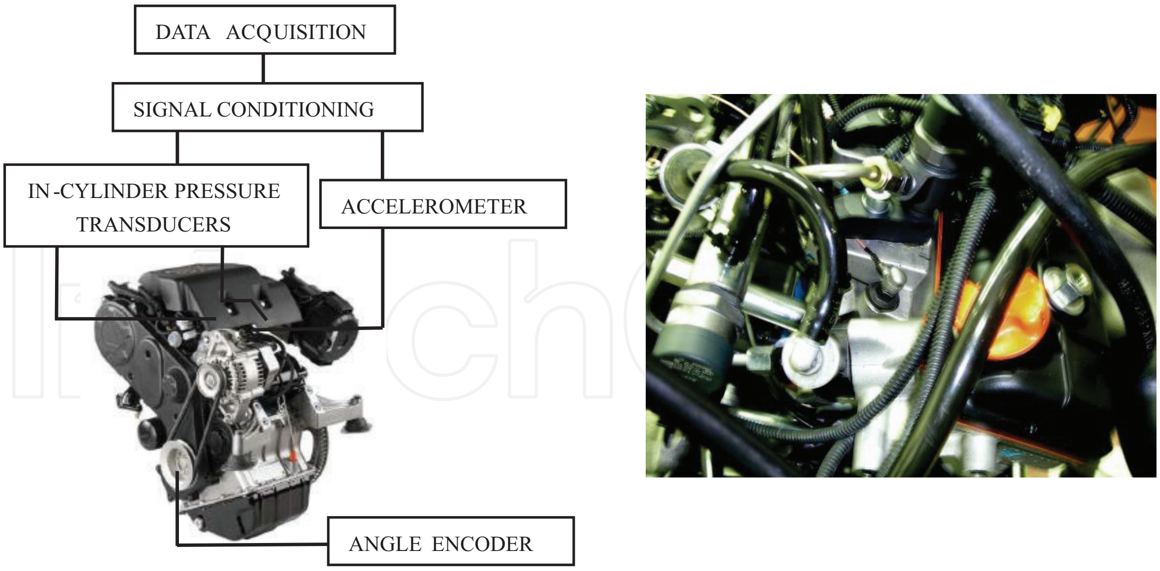

(a) (b)

Figure 1. (a) Engine set up; (b) accelerometer location.

Data acquisition was controlled by means of LabVIEW software, by using self-developed programs. NI board types 6110, 6533, and 6259 were used.

The measurements were performed over the engine speed range 2000–4400 rpm, at different load conditions (from 50% to full load condition). For each running condition, 25 engine cycles were used to average the signal, thus to attenuate the engine cycle irregularities; the increase of such a number did not change the feature of the trends.

All acquisitions started after the engine warm-up, when the engines reached under nominally stationary conditions.

3. Results

This section focuses on the vibration and in-cylinder pressure data processing and it is devoted to describe in detail the developed methodology. In the first part, some representative crank angle evolutions of in-cylinder pressure and accelerometer signals related to naturally aspired configuration are shown and results of frequency domain analysis are presented. In the second part, results obtained with the turbocharged engine configuration are shown.

Figures 2–5 present the time-histories related to naturally aspirated configuration of the engine. The plot of **Figure 2** shows data obtained at 2000 rpm, full load condition with three different injection settings, according to **Table 2**. Case 1 was characterized by two-shot injections (pre and main injections). In cases 2 and 3, multiple injections (pilot, pre, and main injections) were imposed. These cases differentiate for the injection timings.

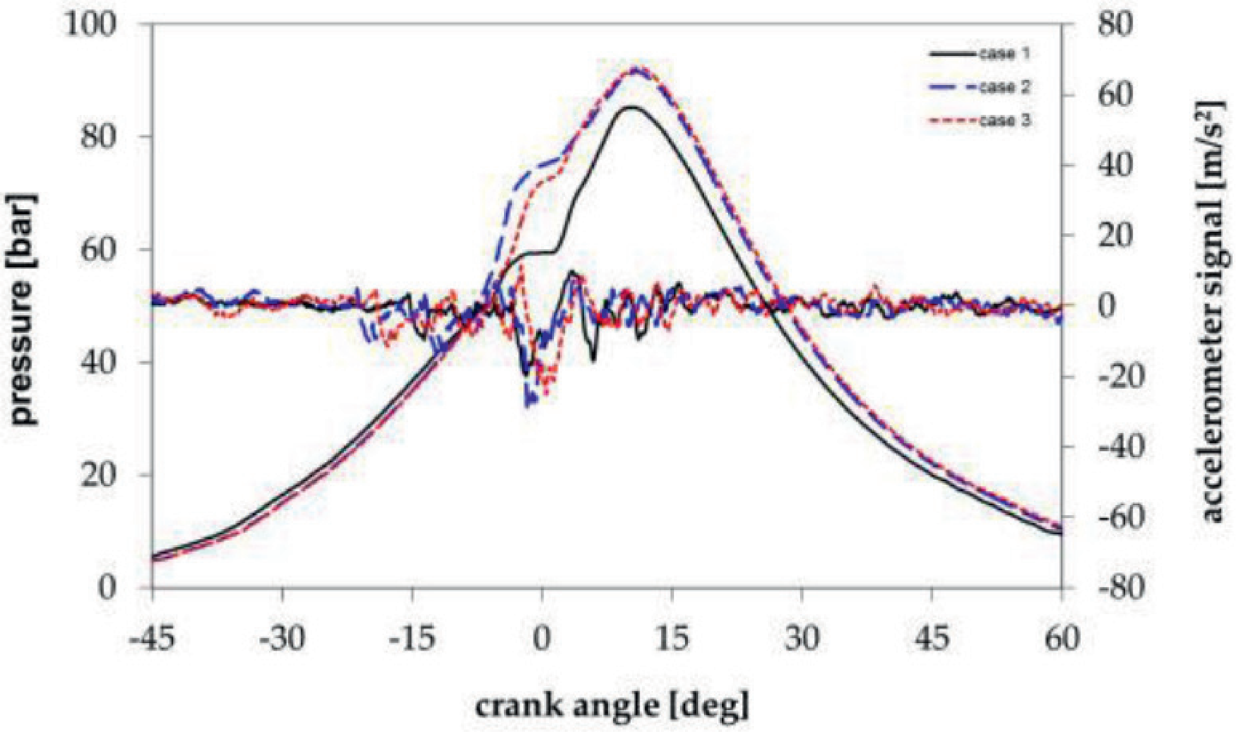

Figure 2. In-cylinder pressure and accelerometer signals at 2000 rpm, 100% load.

In-cylinder pressure traces are superimposed on the corresponding block vibration curves. The accelerometer signals highlight that the mechanical components of the engine vibration (caused by intake and exhaust valve open/close, fuel injection, and piston slap) are less evident than those related to the combustion event.

The abrupt pressure gradient due to the initial air-fuel mixture ignition is responsible for high frequency and high amplitude oscillations in the accelerometer traces, regardless of which injection setting is imposed on the engine.

As the injection parameters change, the in-cylinder pressure development modifies accordingly, and the engine vibration tunes with pressure variations for both the crank angle delay and the maxima amplitude and gradient.

Figure 3 shows the comparison between signals obtained by imposing on the engine a variation of engine speed. The main differences in the pressure development are located at the

	Q [mm^3/cycle]			SOI [crank angle BthC]		
	pil	**pre**	**main**	**pil**	**pre**	**main**
Case 1	0	1	13.5	0	16	6
Case 2	1	1	12.5	24	16	6
Case 3	1	1	12.5	22	13	6

Table 2. Injection data at 2000 rpm, 100% load.

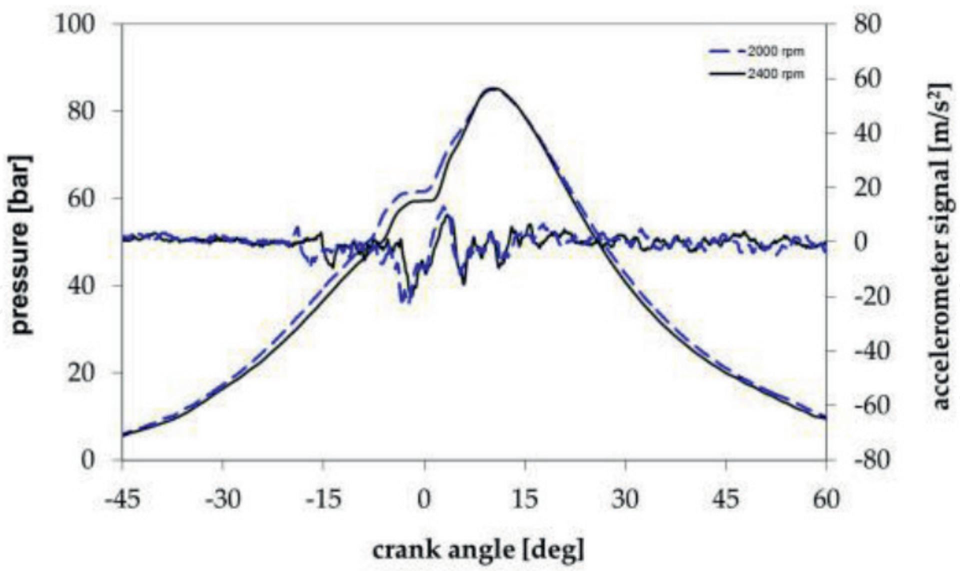

Figure 3. In-cylinder pressure and accelerometer signals at 100% load.

beginning of the combustion process and agree with the variations in the block vibration traces in the same crank angle interval. **Figure 4** shows how the pressure development and block vibration are affected by a variation of the engine load condition. The contribution of combustion process to the vibration traces is evident: accelerometer signals modify in both time and amplitude accordingly with the variations in pressure traces.

Figure 5 shows in-cylinder pressure in one cylinder and block vibration during one complete engine cycle. The plot highlights that the combustion events in both cylinders affect the accelerometer trend (the combustions have 360 crank angle degrees shift). In the crank angle intervals out of those in which combustion processes take place, a low frequency oscillation is exhibited; the frequency of this oscillation is equal to two times the engine speed value. It is to ascribe to engine mechanical components.

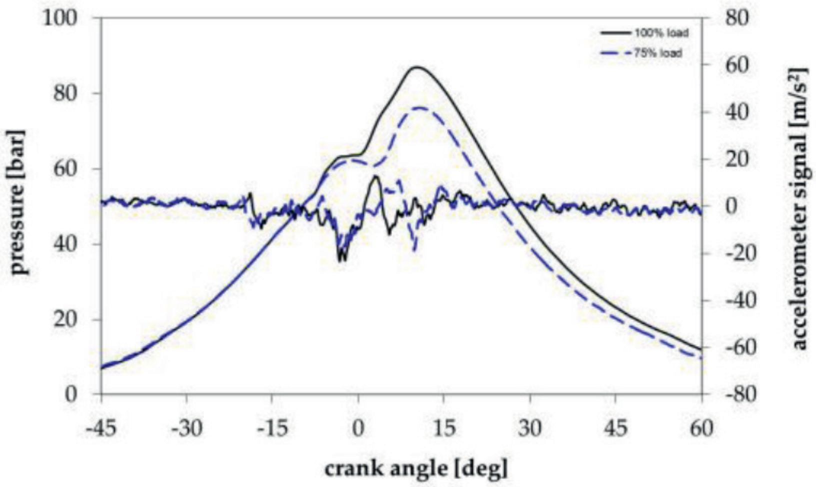

Figure 4. In-cylinder pressure and accelerometer signals at 2400 rpm.

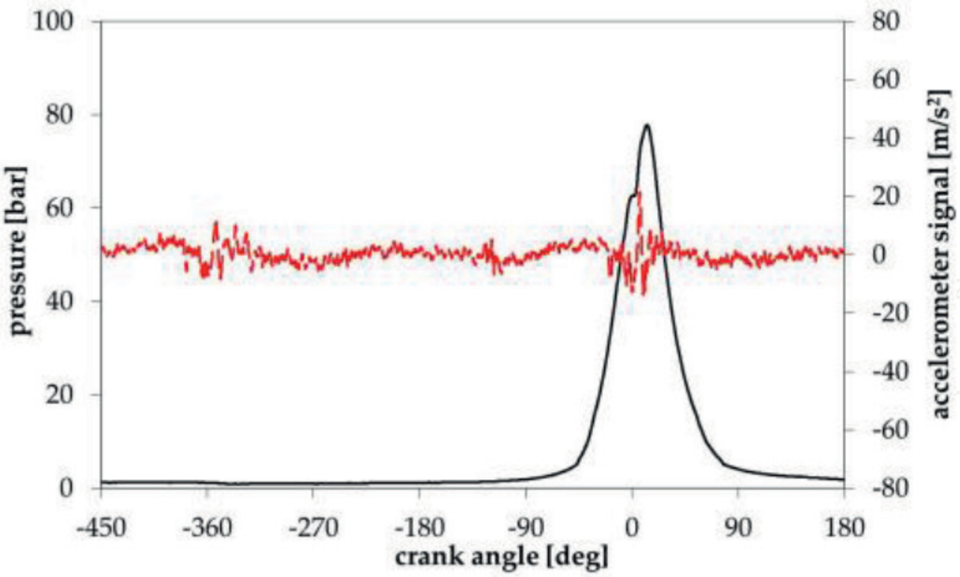

Figure 5. In-cylinder pressure and accelerometer signals at 3200 rpm, 100% load.

In order to insulate the vibration component mainly related to the combustion development, an analysis of the acquired signals in the frequency domain was performed. Coherence function between in-cylinder pressure and acceleration signals was computed. Coherence function is defined as the ratio of the cross power spectral density of an input signal (in-cylinder pressure) and the corresponding output signal (engine block vibration) to the product of the power spectral density of each signal. The function was computed by using windowed data (Hamming window 1/6 of the engine cycle long was used). Further details may be found in Ref. [19].

Figures 6 and **7** show the coherence function trends obtained at 2000 and 2400 rpm, full load condition. The plots highlight that it is possible to define a narrow frequency band

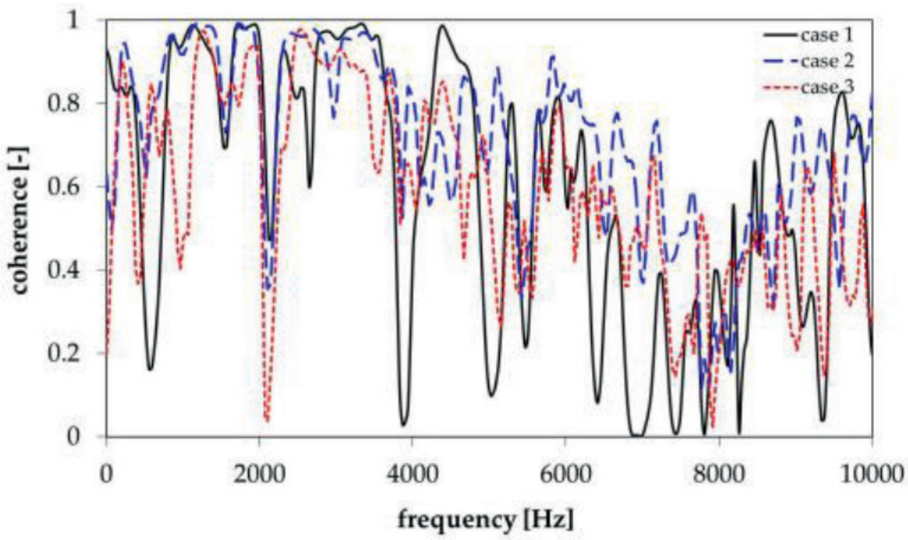

Figure 6. Coherence function at 2000 rpm, 100% load [20].

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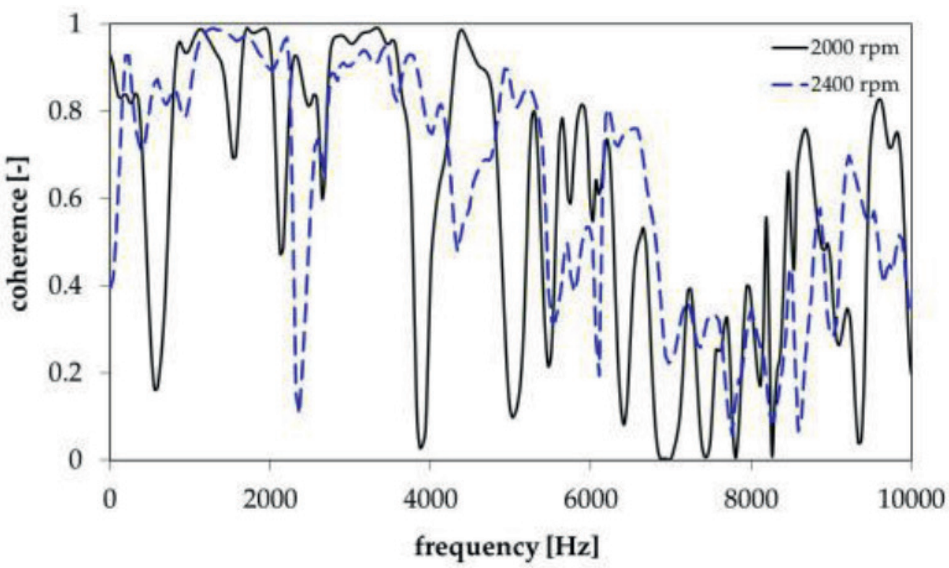

Figure 7. Coherence function at 100% load.

(approximately in the range 1000–2000 Hz) in which coherence function exhibits the highest values. Tests have been performed in order to investigate the effect of engine operative condition on the relation between in-cylinder pressures and block vibration signals. From the analysis of the coherence traces obtained in the engine complete operative field, it came out that no matter which the engine operating condition is, it is always possible to select a range of frequency values in which coherence has the highest values thus showing a linear relationship between in-cylinder pressure and block vibration signals [20, 21]. The processing of the acquired data demonstrated that load condition has a weak effect on the frequency band, whereas it is reliant on the engine speed value, in agreement with results obtained during previous experimental activity [20].

For each engine operative condition, the frequency band, in which in-cylinder pressure and accelerometer traces exhibited high values of correlations, was selected and used to band-pass filter the vibration data, thus allowing to remove from the signal all the components due to sources other than the combustion process.

Figure 8 shows the obtained filtered accelerometer signal related to 3200 rpm, full load condition. The signal is superimposed on the in-cylinder pressure trace; both trends were normalized by dividing all data for the maximum amplitude. The plot highlights oscillations of high amplitude in two-crank angle regions, corresponding to the intervals in which combustion events take place in the cylinders. These oscillations are mainly caused by the combustion since the filtration allowed to keep into the signal only the components highly correlated to the combustion.

Aimed at relating the combustion process to the filtered accelerometer trace, the rate of heat release (ROHR) was computed starting from the in-cylinder pressure, through a thermodynamic model in which the Woschni model was used for the instantaneous heat loss to the cylinder wall.

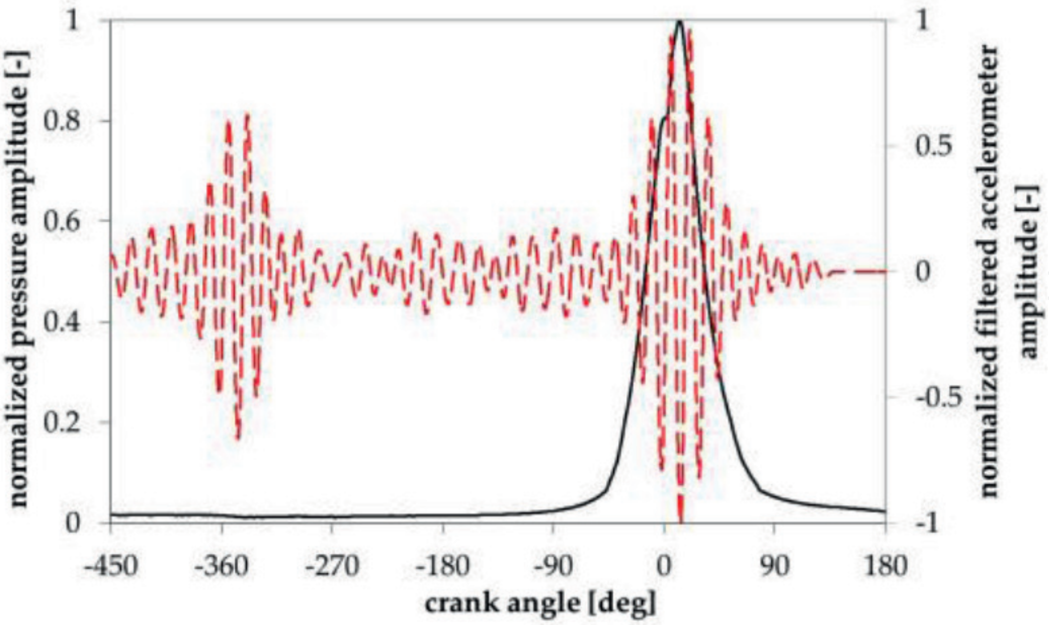

Figure 8. Normalized in-cylinder pressure and filtered accelerometer signals at 3200 rpm, 100% load.

Figure 9 shows the ROHR trace superimposed on the accelerometer signal for 3200 rpm, full load condition. Data were normalized with the maximum value. The circle in the plot highlights a zero crossing in the accelerometer trace that indicates the crank angle value corresponding to the start of combustion (SOC).

Starting from the ROHR, the cumulative heat release (CHR) was computed aimed at evaluating the crank angle values corresponding to the burnt mass fraction. **Figure 10** shows the CHR and the filtered accelerometer trend; circles are used to point out SOC and the angular position at which half of the injected fuel is burnt (MFB50).

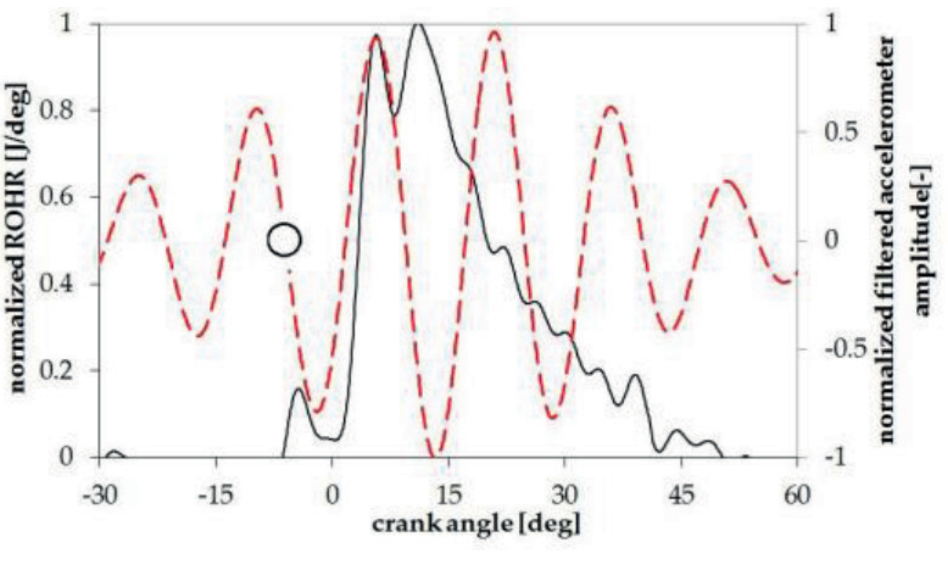

Figure 9. Normalized rate of heat release and filtered accelerometer trends at 3200 rpm, 100% load.

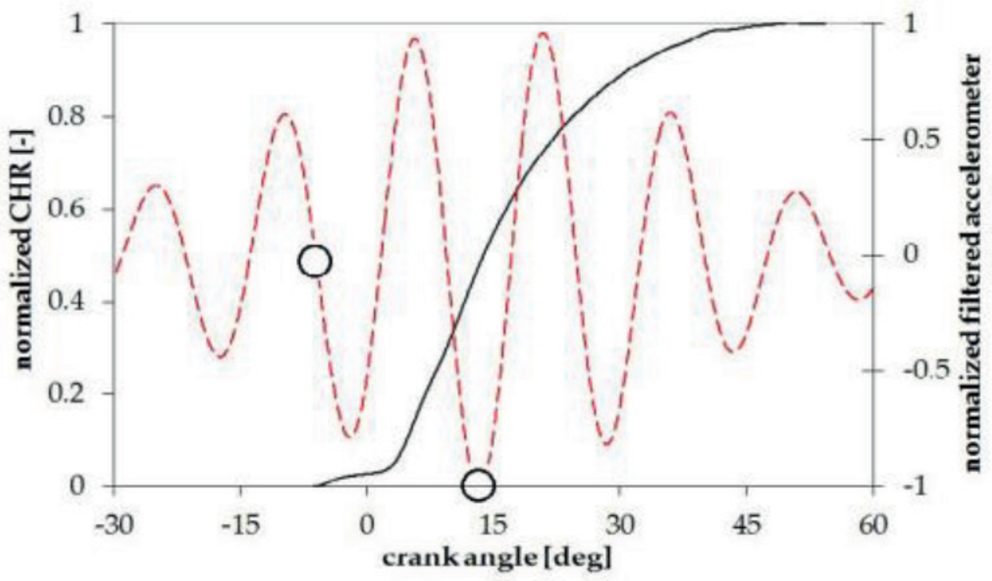

Figure 10. Normalized cumulated sum of rate of heat release and filtered accelerometer trends at 3200 rpm, 100% load.

The same processing was performed with the signals acquired with turbocharged engine configuration. **Figure 11** presents the crank angle evolution of in-cylinder pressure and accelerometer trace at 4000 rpm, 100% load.

The vibration trace appears more noisy in comparison with that one obtained during tests with naturally aspirated configuration (i.e., signals are shown in **Figures 2** and **3**), but the effect of combustion process on the accelerometer signal is evident, as shown in **Figure 12**. In the plot, the vibration signal acquired in fired condition is compared to that one related to the same engine condition but obtained with naturally aspirated configuration. The trace related to motored test at the same value of engine speed is also shown.

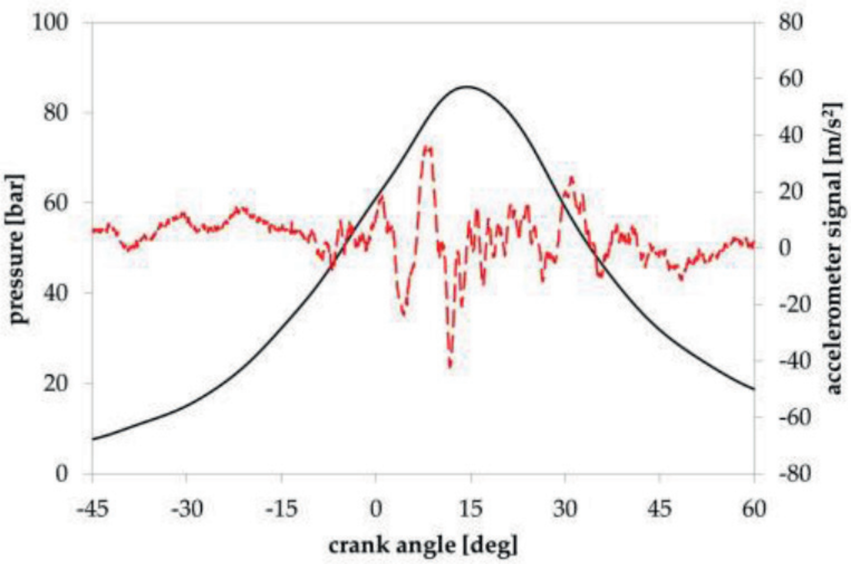

Figure 11. In-cylinder pressure and accelerometer signals at 4000 rpm, 100% load (turbocharged).

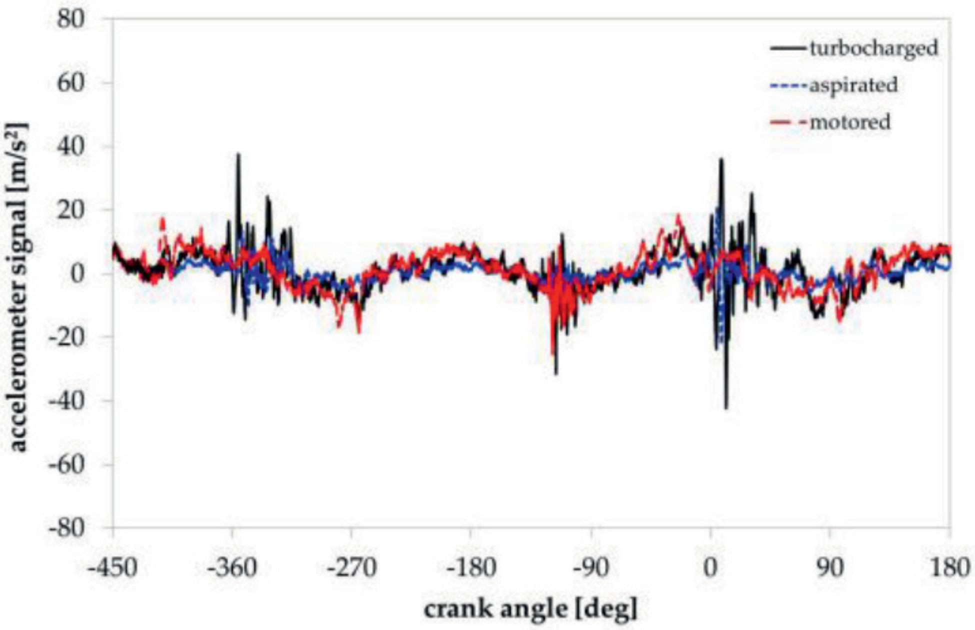

Figure 12. Accelerometer signals at 4000 rpm.

An analysis in the frequency domain of the data acquired with turbocharged configuration was performed and the frequency band in which in-cylinder pressure and accelerometer traces are highly correlated was evaluated. Starting from in-cylinder pressure data, ROHR, and CHR were computed (they are shown in **Figures 13** and **14**, respectively). In the plots, the data are superimposed on the vibration signal that was band-pass filtered according to the results of coherence function analysis. Circles are used to highlight in the accelerometer trace the crank angle values corresponding to the SOC and MFB50.

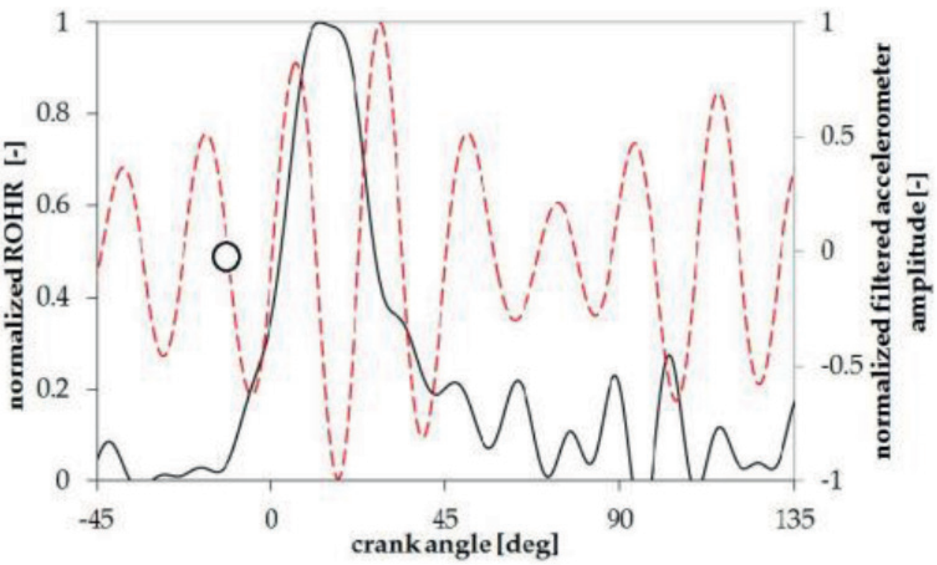

Figure 13. Normalized rate of heat release and filtered accelerometer trends at 4000 rpm, 100% load (turbocharged).

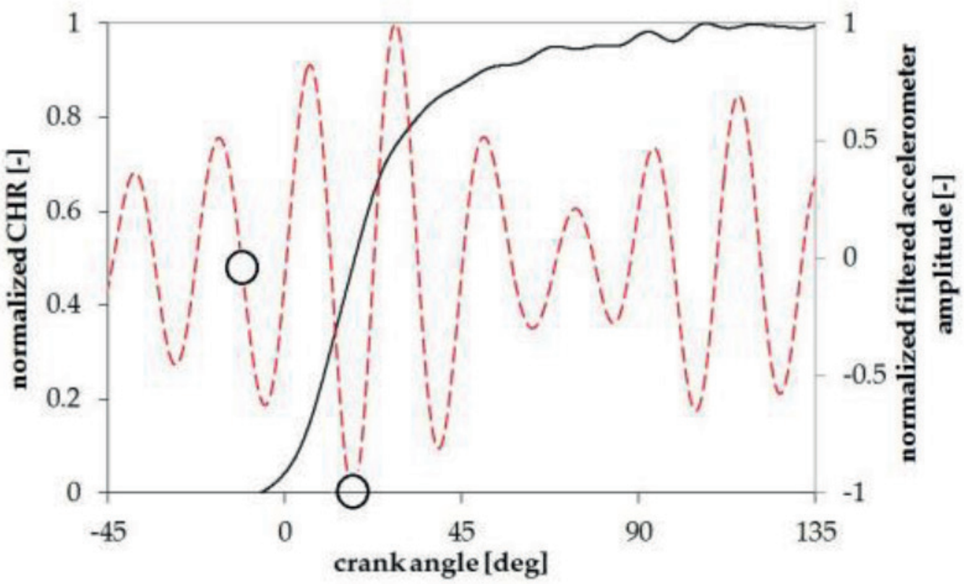

Figure 14. Normalized cumulated sum of rate of heat release and filtered accelerometer trends at 4000 rpm, 100% load (turbocharged).

Figures 15 and **16** show comprehensive plots of results obtained for naturally aspirated and turbocharged engine configuration, respectively.

In each figure, SOC and MFB50 are reported for 3600, 4000, and 4400 rpm, 60, 75, and 100 % load. Data on the *x*-axis show the crank angle value computed via CHR. Crank angle values in the *y*-axis were computed via filtered accelerometer trace.

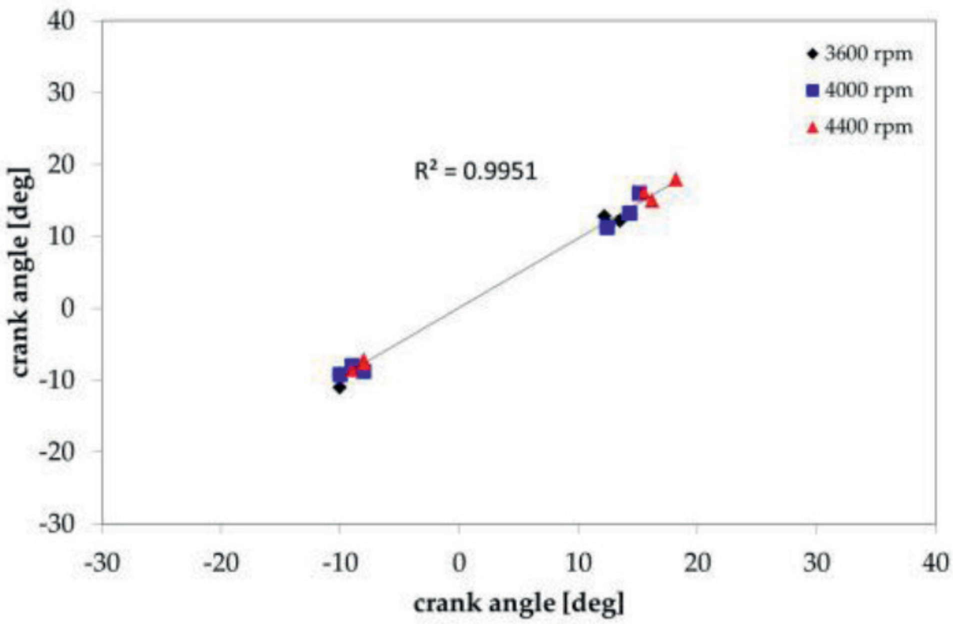

Figure 15. SOC and MFB50 for naturally aspirated engine configuration.

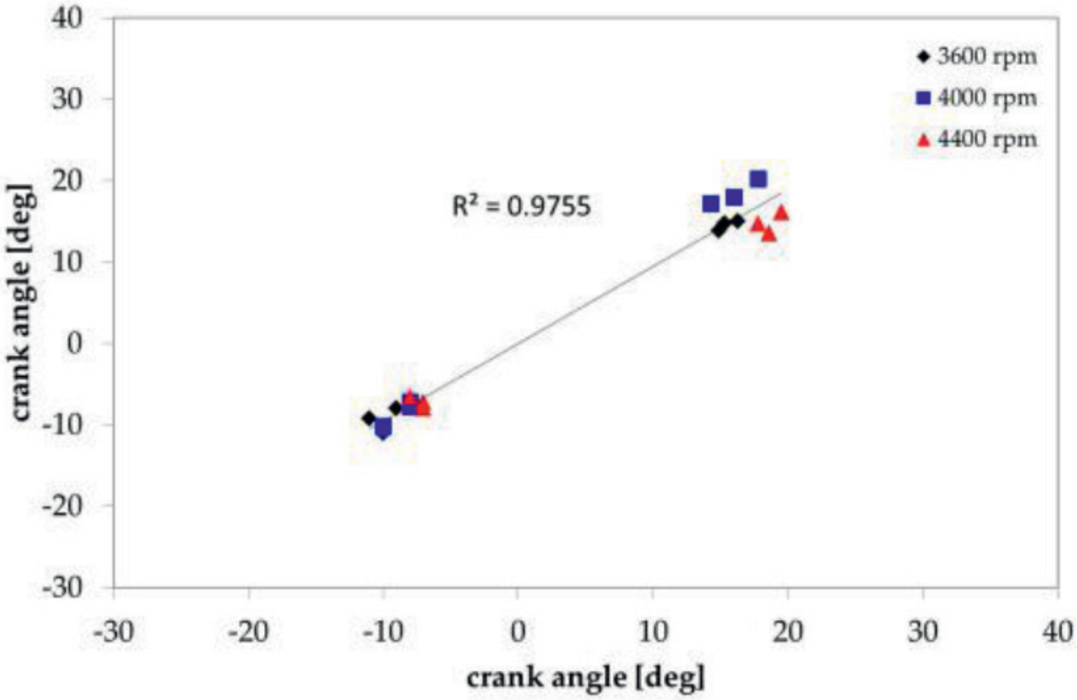

Figure 16. SOC and MFB50 for turbocharged engine.

In both plots, the interpolation lines and the corresponding R-squared values are shown (they are the square of the correlation coefficients).The obtained R values are in all cases very close to the unity, giving a measure of the very high reliability of the relationship between the combustion indicators estimated via accelerometer transducer and computed by direct in-cylinder pressure measurements.

4. Conclusion

A methodology was developed and validated, aimed at extracting from the signal of an accelerometer placed on a selected location of the engine block information about the combustion process in a diesel engine.

Experimentation was performed on a two-cylinder common rail diesel engine; two configurations were tested: naturally aspirated and turbocharged.

The analysis of the signals acquired in the engine complete operative field highlighted that it is always possible to select a frequency band in which in-cylinder pressure and engine block vibration signals are highly correlated. Such a band has demonstrated to be reliant on the engine speed value, whereas load condition has a weak effect on the frequency band, in agreement with results obtained during previous investigations.

The accelerometer signals were filtered in order to remove all the vibration components due to sources other than the combustion. The obtained combustion-related vibration contributions were used to evaluate indicators able to characterize the combustion development. The angular position of SOC and MFB50 was thus computed via processed accelerometer traces and compared to the same indicators evaluated via the heat release curve. The obtained data highlighted the high reliability of the methodology and indicated its prospective applicability in the real-time control of the engine management, in which the control algorithm manages the injection control unit based only on nonintrusive measurement. The comparison between combustion indicators evaluated only by means of the block vibration trend is compared to the optimal values stored in maps previously filled with data for each engine running conditions. The results of such a comparison are used as feedback signal to correct the injection settings.

Nomenclature

BTDC	Before top dead center
CDM	Code division multiplexing
CHR	Cumulative heat release
deg	Degree
main	Main injection
MFB50	Angular position at which half of the injected fuel is burnt
pil	Pilot injection
pre	Pre-injection
Q	Injected fuel
R	Correlation coefficient
ROHR	Rate of heat release
SOI	Angular position at which injection starts
SOC	Angular position at which combustion starts
TTL	Transistor-transistor logic

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