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Diagnostic methodology for internal combustion diesel engines via noise radiation

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ABSTRACT

This paper presents an experimental methodology to obtain information about the in-cylinder pressure development during the combustion process of a small displacement diesel engine by using the acoustic emission.

The research activity arises from two considerations. On one end, an efficient control of the combustion process has demonstrated to be crucial to ensure complying with increasingly emerging diesel emission standards and to reduce fuel consumption. On the other end, even if nowadays the employment of in-cylinder pressure sensors in combustion control techniques appears to be a very promising technology, solutions based on non-intrusive methodologies offer the indubitable advantages of guaranteeing the absence of any interaction with the engine operation. Furthermore, these solutions allow the sensor to be installed in any kind of production engine without the need of modification.

In the present paper, the engine noise emissions have been analyzed with the aim to extract the combustion related contribution. Particular attention has been devoted to the definition of indicators able to characterize both the noise and the in-cylinder pressure development. The relationship between these indices in the entire engine operative field allowed to evaluate the combustion properties by using only the sound radiation signal as input.

1. Introduction

The tightening of the regulations on exhaust emissions and noise radiations has posed serious challenges to the researchers and engine manufactures to find out solutions capable to ensure compliance with the new limits without affecting the engine performance.

In light of the relationship existing among the different needs, advanced methods are required to control the in-cylinder pressure development during the combustion process [1,2].

The combustion control strategies allow to efficiently correct the injection parameters in order to guarantee the real-time optimization of the process. Even if nowadays, the employment of in-cylinder pressure sensors in combustion control techniques appears to be a very promising technology, thanks to the newly developed piezo-resistive sensors, the employment of solutions based on non-intrusive methodologies offers the indubitable advantage of avoiding any possible interaction with the engine operation; furthermore, the sensors can be mounted in any kind of production engine without the need of modification.

Most of on-board non-intrusive strategies that have been successfully implemented are based on crankshaft angular speed and vibration measurements.

When the combustion process takes place in each cylinder of the engine, the combustion torque becomes greater than the external torque and is then responsible for the crankshaft acceleration. During the compression phase, the torque drops down below the external torque and then the crankshaft decreases its speed. These phenomena result in a fluctuating waveform of the engine speed that can be used to extract information about the combustion process. The monitoring of diesel engine by analyzing the crankshaft angular speed variations has drawn much of attention in the past years. In [3] correlations existing between torque and speed frequency components are analyzed; in [4], the crankshaft angular speed measurements are used for combustion-related faults diagnosis.

The methodologies based on the vibration signal analysis aim at establishing a relationship between the combustion event and the response of an accelerometer. The rapid increase of the pressure in the cylinder during the combustion gives rise to engine structure vibrations. These vibrations contain information about the combustion process but also comprise non-combustion related components that decrease the signal-to-noise ratio. Research activities

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Nomenclature

BTDC	before top dead center
CHR	cumulated heat release
CI	combustion index
deg CA	crank angle degree
ECN	end of combustion noise
ECU	electronic control unit
EVC	exhaust valve closing
EVO	exhaust valve opening
F	delivered fuel quantity
IVC	intake valve closing
IVO	intake valve opening
MBF50	crank angle degree of 50% mass burned
MBF100	crank angle degree of 100% mass burned
MPRR	maximum pressure rise rate
NI	noise index
P	pressure
PSD	power spectral density
R	coefficient of correlation
ROHR	rate of heat release
SCN	start of combustion noise
SOI	start of injection
str	stroke
Q	heat release
V	in-cylinder volume
γ	specific heat ratio
α	crank-angle

Subscripts

c	cylinder
main	main injection process
pre	pre-injection process
rail	common rail of the injection system

have been focused on the detection of combustion characteristics via the employment of accelerometers in multiple placements and orientations in the engine [5]. In [6], a non-linear model is proposed for the reconstruction of in-cylinder pressure pulse waveforms. In [7], a method is presented to separate the accelerometer mixed vibration sources, while in [8] a 6-cylinder engine is tested in order to estimate the combustion signature and to sense combustion faults. In [9,10], the engine block vibration signal of a small displacement diesel engine is analyzed and the relationship between the in-cylinder pressure and the vibration trace during stationary and transient operation is highlighted.

The condition monitoring of diesel engine via its acoustic emissions has received scant attention in the past, due to the difficulties of extracting useful information from the acquired data stemming from the high concentration and overlapping both in time and frequency domains of the different sources.

Internal combustion engines produce a complex noise, whose level and sound quality are strongly reliant on the engine type of combustion, architecture. It was highlighted that many sources contribute to the overall noise radiated by an engine: injection, combustion, piston slap, turbocharger, oil pump, valves, inlet and exhaust fluid-induced noise, etc. Diesel engine combustion noise is due to the self-ignition of the fuel that produces a sudden rise of pressure in the combustion chamber. This excitation is responsible for the block vibration and thus noise radiation. The engine structure has an important role in the attenuation of the emission and its design is critical for the engine noise performance improvement. There are many patterns of sound energy propagation through the engine block and its behavior has demonstrated to be time-variant and non-linear [11,12].

In recent years, many researchers have focused on the investigation of diesel engine noise emission and on the separation of the different sources contributing to the overall radiation [13–15].

Experimental works have been devoted to diagnose engine faults via acoustic measurements [16,17]. In [18], a method is proposed to extract information about injection condition from airborne acoustic signals. In [12], the in-cylinder pressure evolution is decomposed into pseudo-motored, combustion and resonance components: the technique is applied to combustion noise analysis. In [19], the noise radiation is investigated during steady state and transient running conditions of the engine; the aim was to evaluate its correlation with the in-cylinder pressure measurement that allows noise prediction starting from in-cylinder pressure measurements. [20] is devoted to investigate the effects of different gaseous fuels and operating parameters on combustion noise. In [21] the mechanism of combustion noise emission is investigated under various transient schedules. In [22,23], the sound generation of a diesel engine is modeled based on the cylinder pressure curve and it is used to monitor the engine condition. In [24], a method is proposed to identify dominant noise source locations of a diesel engine. In [25], the combustion noise is analyzed by measuring the in-cylinder pressure and the engine noise; furthermore, an index is proposed to evaluate the combustion noise, that is based on the cylinder pressure measurement.

This paper presents the main results of a research activity that is based on the observation that the engine acoustic signal may have a strong correlation with the combustion process. The paper aims at demonstrating the applicability of a new methodology that makes possible to realize a real time management of the control unit, relating the sound emission back to the combustion process development.

In the first phase of the activity, the optimal position of the transducer was selected by analyzing the combustion acoustic emission signal to noise (the acoustic signal content due to other sources) ratio. The location was chosen by comparing the microphone signal with the in-cylinder pressure trace (acquired by an transducer placed inside the combustion chamber) and by analyzing in detail the temporal evolution of the acoustic signal in which the combustion contribution is superimposed by many other information [26].

Once the optimal microphone placement was individuated, the measurements were devoted to better understand the relationship between noise emission and in-cylinder pressure development during the combustion process. The spectral levels of both radiated noise and in-cylinder pressure were analyzed and the spectrograms were computed, in order to highlight the relevant aspects of the correlation between the signals. The characterization of the signals in the frequency domain allowed to extract from the noise emission the frequency components mainly caused by the combustion process and to define some indices able to relate the radiated noise with the combustion process.

2. Experimental equipment

Tests were performed in a non-anechoic chamber in the Engineering Dept. Laboratory of ROMA TRE University, without special acoustic monitoring precaution. The tested engine was a naturally aspirated, two-cylinder, water-cooled Lombardini LDW442CRS

Table 1
Main specifications of the tested engine.

Engine specifications	
Engine type	LDW442CRS naturally aspirated
Cylinders	2
Displacement	440 cm3
Bore	68 mm
Stroke	60.6 mm
Compression ratio	20:1
Maximum power	8.5 kW @ 4400 rpm
Maximum torque	25 Nm @ 2000 rpm

diesel engine, equipped with a common rail injection system. The engine, whose main technical data are reported in Table 1, is mainly used for microcars, small commercial and leisure vehicles applications.

A fully opened electronic control unit (ECU) was used to manage the engine during the experimentation. The ECU allowed to control the injection system settings (injection strategy, timing and duration of each shot).

The engine was coupled with an asynchronous motor (SIEMENS 1PH7, nominal torque 360 Nm and power 70 kW). Its control system (SIEMENS SINAMICS S120) allowed to manage engine speed or load during tests. Fig. 1 shows the complete engine set-up.

A Bruel and Kjaer Free-field ¼-in. microphone type 4939, with associated preamplifier type 2670, was used to acquire the acoustic emission (Fig. 2 highlights the microphone location, whereas Table 2 reports the transducer specifications). The signal was conditioned by means of Nexus 2693-A device.

A piezoelectric transducer AVL GU13P was used to measure the instantaneous in-cylinder pressure (the preheating plug was substituted by the pressure probe).

Engine crank angle position tracking was performed using an optical encoder AVL 364C. During the tests, the sampling rate was varied according to the engine speed value in order to guarantee a fixed angular resolution (0.125 crank angle degree (deg CA)).

Additional sensors were installed with the aim of monitoring the engine running conditions (pressure and temperature transducers along the intake and exhaust systems, exhaust gas analyzer, fuel consumption and intake mass flow measurements).

All the fast changing signals were simultaneously acquired by NI boards type 6110 (analogical signals) and 6533 (digital signals); all the slow changing signals were acquired by means of NI board

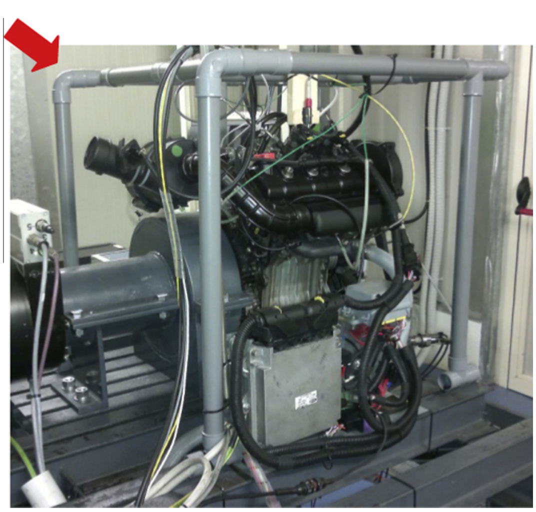

Fig. 1. Test-bench (the red arrow indicates the network used for microphone positioning). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

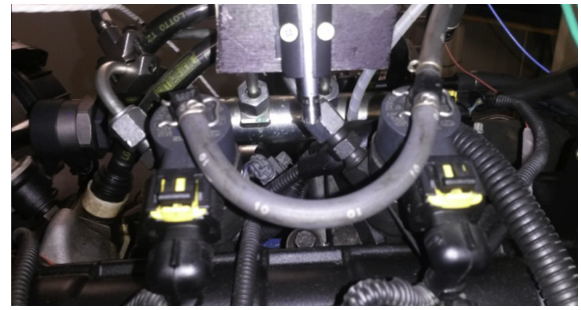

Fig. 2. Detail of the microphone position.

Table 2
Microphone specifications.

Microphone specifications	
Type	B&K 4939
Sensitivity	4 mV/Pa
Temperature	−40 to 150 °C
Frequency	4–100,000 Hz

type 6259. A software was developed by the authors in LabVIEW environment for both signals monitoring and acquisition.

A first series of experiments was performed for motored and fired conditions in order to select the optimal location for the microphone. Since the signal has shown to be highly contaminated due to the adverse acoustic environmental, a network that encircles the engine was mounted, thus allowing to guarantee the repetitiveness of each test. The network was placed at a distance of about 5 cm from the cylinder head (Fig. 1). Measurements were carried out by the microphone in different positions and the results were compared under the same test conditions.

3. Test conditions

The measurements were performed over the engine speed range 2000–3600 rpm, at different load levels (from 50% to 100%). For each engine speed and load value, the measurements were performed by imposing on the engine a variation of the injection setting. The programmable electronic control unit, connected to a PC, was used to set the engine injection parameters. Five series of tests were executed, named ‘mode 1’ to ‘mode 5’ (Table 3 displays the characteristics of each test related to the condition 2000 rpm, full load). A two-pulse injection mode was used for all engine operation range: mode 1 and 2 were characterized by a variation of the pre-injected fuel quantity (and thus of the main injected quantity since the total amount of delivered fuel remained always the same during all tests). Mode 3 was characterized by an advance of the pre-injection timing, respect to mode 1 and 2.

During mode 4, an injection timing advance of both shots was imposed on the engine with respect to mode 1; mode 5 was

Table 3
Test cases: 2000 rpm, full load.

	Test cases: 2000 rpm, full load				
Mode	1	2	3	4	5
P_{rail} (bar)	700	700	700	700	700
F_{pre} (mm^3/str)	1	2	1	1	1
F_{main} (mm^3/str)	13	12	13	13	13
SOI_{pre} (deg CA BTDC)	16	16	20	20	13
SOI_{main} (deg CA BTDC)	6	6	6	8	5

characterized by a delay of both pre and main injection process with respect to mode 1.

Tests were started only after temperatures of oil and coolant reached normal operating conditions (engine warm up); data were collected only after the engine had reached nominally stationary conditions.

4. Characterization of the combustion process via engine acoustic radiation

The following sections are devoted to investigate in detail the existence of relationship between the in-cylinder pressure trace during the combustion process and the engine noise emission. Once the correlation between the signals was established, the research was focused on the definition of indices able to characterize both the combustion process and the noise radiation and on the assessment of a possible correlation between them, in order to characterize the combustion process via its related noise emission.

4.1. Relationship between acquired signals

Fig. 3 presents the crank angle evolutions of the in-cylinder pressure trace and the acoustic radiation acquired during tests in which the engine was running at 2000 rpm, full load and at motored conditions. Such a condition was performed by disabling the ECU (thus deactivating the electro-injectors) once the engine was warmed up and letting the asynchronous motor to drive the engine. In this way, during motored conditions, the engine run at the same speed as that imposed during fired conditions so as to maintain unchanged the mechanical components of the noise emission.

All the acquired signals were averaged based on 10 cycles, in order to attenuate the presence of the engine cyclic irregularities.

As the plot highlights, the engine radiation was characterized by a low frequency fluctuation that corresponded to the 2-nd harmonic of the combustion frequency, also during a motored test.

In Fig. 4, the comparison of the acoustic radiation spectrum for fired and motored conditions in the low frequency range is highlighted (the combustion frequency corresponds to 33.3 Hz).

With regard to the high frequency components visible in Fig. 3, it can be observed that many overlapped sources contributed to the overall acoustic signal. Among them, the components caused by the combustion process are clearly noticeable by comparing the motored with the fired curves. In the investigated engine, the combustion events were spaced 360 deg CA apart. As the emission signal demonstrates, the microphone was able to sense the combustion processes in both cylinders.

The following Figs. 5 and 6 show the comparison between the pressure and the acoustic signals obtained by imposing a variation

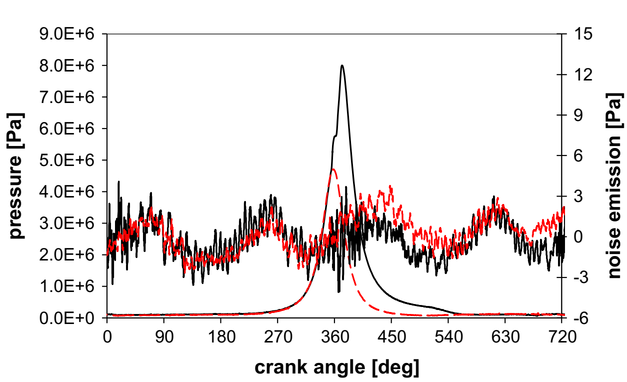

Fig. 3. In-cylinder pressure and noise emission at 2000 rpm: —— full load, ······ motored.

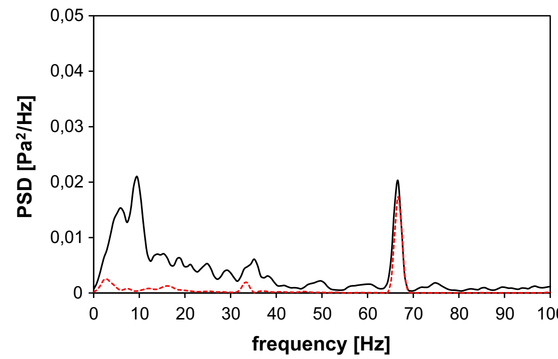

Fig. 4. Acoustic radiation spectrum in the low frequency range at 2000 rpm: —— full load, ······ motored.

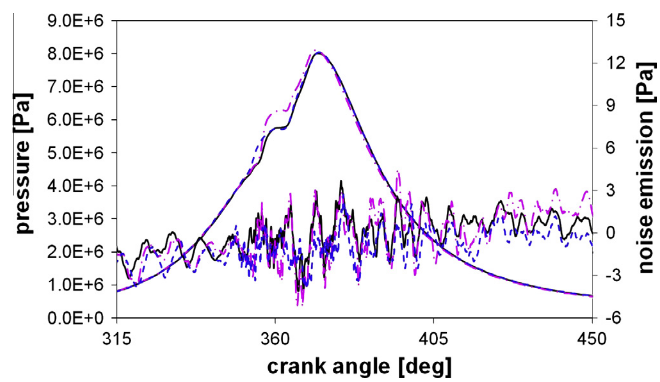

Fig. 5. In-cylinder pressure and noise emission at 2000 rpm, full load: —— mode 1, — · mode 2, — — mode 3.

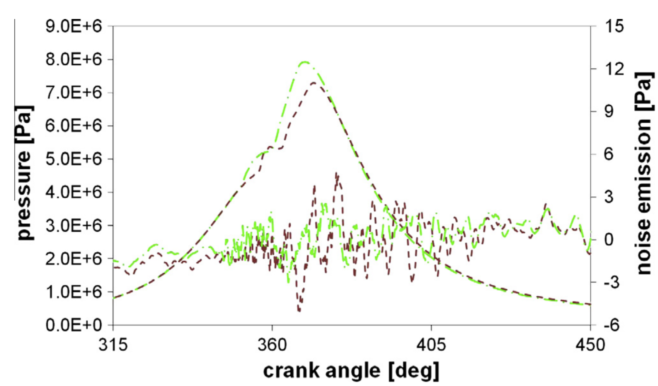

Fig. 6. In-cylinder pressure and noise emission at 2000 rpm, full load: — · mode 4, — — mode 5.

of the injection strategy on the engine (only a part of the cycle is depicted, in order to highlight the crank angle interval before the combustion process and the effect on the acoustic emission of the combustion process variation caused by different injection parameters).

It can be noted that, depending on the injection settings, the pressure development changes; the noise emission signals also change accordingly, for what concerns both the crank angle delay and the signals amplitude:

– the highest pressure gradient caused by the largest amount of fuel delivered during the pre-injection process of mode 2 with respect to the other tests is responsible for the highest acoustic amplitude;

– the comparison between the in-cylinder pressure data related to modes 3, 4 and 5 with the corresponding acoustic signals highlights the effect of the variation of the injection timings on the pressure development and then on the noise radiation during the combustion process.

The figures demonstrate that the microphone was able to sense the combustion process whatever injection strategy imposed on the engine.

The obtained trends suggest the potential employment of the microphone as feedback signal in a non-intrusive diagnostic and control tool for the combustion process.

In order to provide a deeper insight into the signals so as to realize a reliable methodology, the frequency analysis of the acquired data was performed aimed at characterizing the acoustic emission components and relating them to the spectral content of the combustion source.

The analysis was performed by following the same path as in a previous research activity, in which the in-cylinder pressure signal during the combustion process was characterized by means of the engine block vibration signal. The filtration in a properly defined frequency band allowed to keep into the vibration signal only the contributions mainly related to the combustion process. The implemented methodology is described in detail in [27].

The following figures present some representative results of the acquired signal frequency domain analysis. Fig. 7a shows the comparison between the spectra associated with the pressure evolution in one cylinder at 2000 rpm, at full load and motored conditions (that is assumed as the reference signal). From the frequency decomposition, the three phenomena taking place during diesel engine operation are highlighted: motored, combustion and resonance excitation [12]. In the low frequency range region of the spectrum, the amplitude of the components is dominated by the motored condition and depends on the engine operating parameters (load and speed); the energy is distributed among the harmonics of the fundamental frequency for both the engine conditions. The power spectral density (PSD) slope in the middle-frequency range depends on the rise rate of the cylinder pressure. The PSD content in this frequency region is strictly connected to the injection parameters setting and it is defined as the combustion noise region [19]. In the high-frequency range, the peaks are due to the rapid increase of the in-cylinder pressure at the beginning of the combustion process. The comparison between the traces highlights the very low energy distribution in the middle-high frequency fields in the spectrum of motored conditions with respect to that one with combustion. The plot points out that the main changes in the pressure spectrum caused by the combustion process appear at middle frequencies; therefore, combustion noise should consider frequencies above 300 Hz.

In the high-frequency range, a cut-off frequency (about 1.5 kHz) can be observed from which the pressure amplitudes tend to increase. This indicates the occurrence of a resonance phenomenon induced by the pressure oscillations of the burned gases in the combustion chamber.

The analysis of the traces obtained by imposing a variation of the injection parameters confirms the lower limit of frequency (approximately 300 Hz) at which the combustion process is responsible for a significant modification of the energy distribution in the in-cylinder pressure signal with respect to motored conditions.

Once the excitation source responsible for the combustion noise emission was characterized, the radiated noise was investigated with the aim of better understanding the relation between the signals.

Fig. 7b shows the engine noise emission spectra obtained during measurements with and without combustion. These traces can be compared to the corresponding in-cylinder pressure spectra of Fig. 7a. It is possible to observe that the contribution of the combustion process on noise emissions takes place in a wider frequency band than that one characterizing the in-cylinder pressure spectrum in fired conditions.

This feature is due to the presence of many patterns of sound energy propagation through the engine block, that is a non-linear and time-variant system [11,12].

In order to obtain information about the time distribution of the spectral energy of the in-cylinder pressure and of the noise emission, the spectrogram of the signals was computed. Figs. 8 and 9 show the spectrograms of pressure and noise emission, respectively (engine condition 2000 rpm, full load). Figs. 10 and 11 present the spectrograms of in-cylinder pressure and radiated engine noise, respectively, under motored conditions.

In all figures, the in-cylinder pressure development is also shown in order to make easier to understand the data.

In the spectrograms, the intake and exhaust valve timings are also reported, to highlight their contribution in the overall engine radiation (1 and 2 are respectively used to indicate the cylinder in which the pressure transducer was installed and the non-instrumented one).

The comparison between the spectrograms of the pressure signals reveals the contribution in the frequency domain of fuel injection and combustion processes (motored engine was obtained by disabling ECU). The analysis of the spectrograms obtained by imposing a variation of the injection parameter settings (according to Table 3) highlights an agreement between the temporal distribution of spectral components and the pressure development.

The noise spectrograms obtained for motored and fired engine conditions exhibit a periodicity of the sources contributing to the overall emission. In the spectrogram of noise emission during fired conditions, the presence of the combustion contribution of both cylinder can be clearly distinguished (the related noise components are concentrated in the crank angle intervals around 360 and 720 deg CA). The combustion processes are responsible for

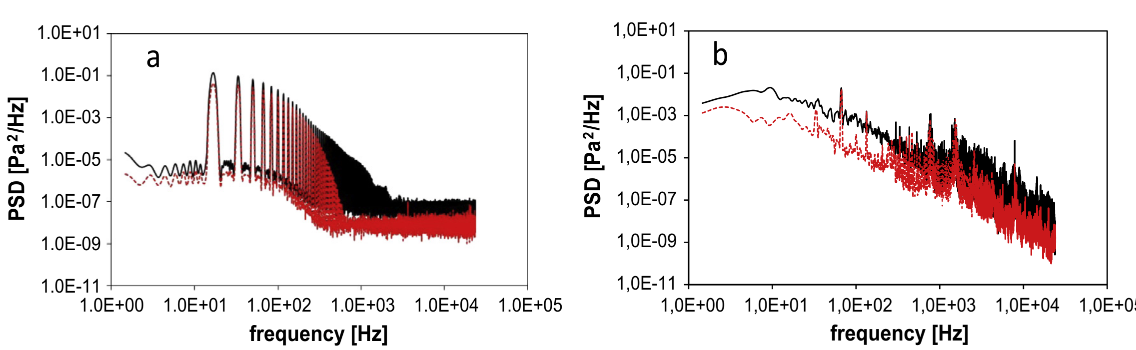

Fig. 7. (a) In-cylinder pressure PSD; (b) noise emission PSD at 2000 rpm: —— full load, ······ motored.

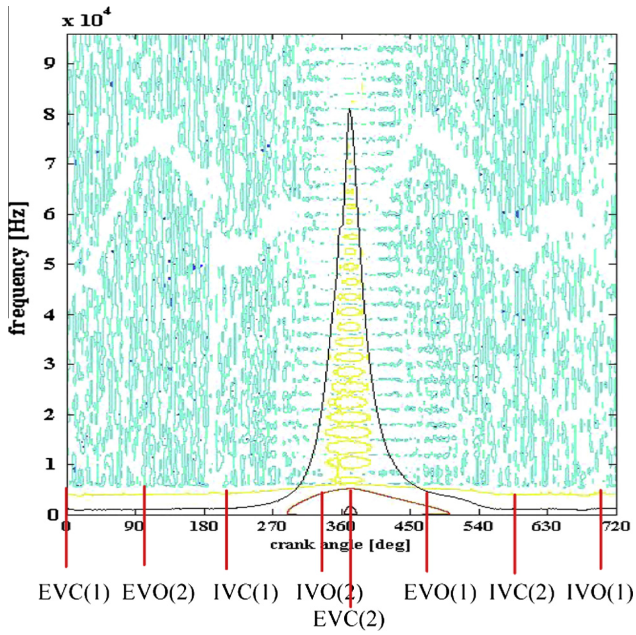

Fig. 8. In-cylinder pressure spectrogram at 2000 rpm, full load, mode 1; —— pressure-crank angle evolution.

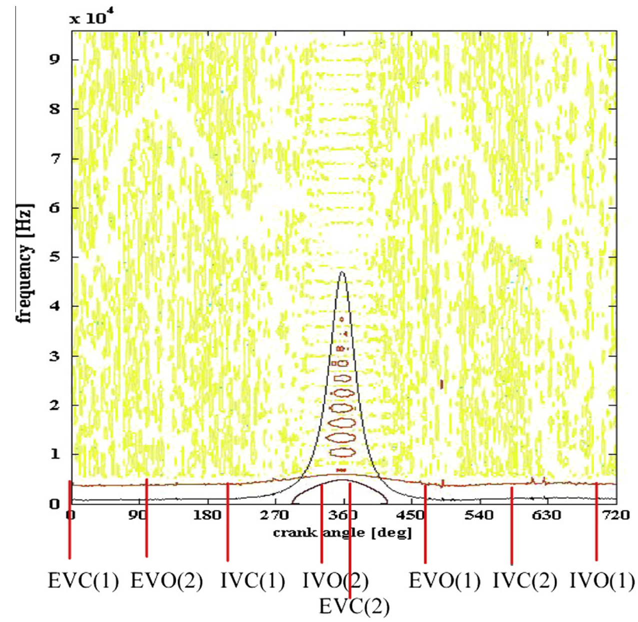

Fig. 10. Motored in-cylinder pressure spectrogram at 2000 rpm; —— pressure-crank angle evolution.

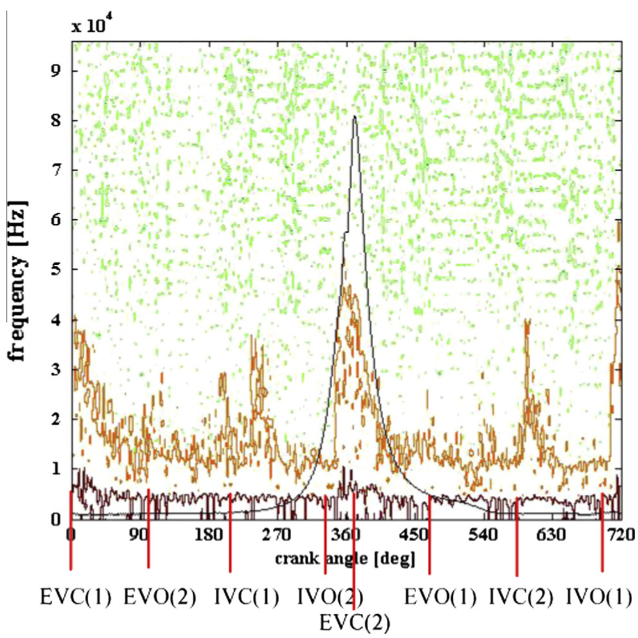

Fig. 9. Engine noise spectrogram at 2000 rpm, full load, mode 1; —— pressure-crank angle evolution.

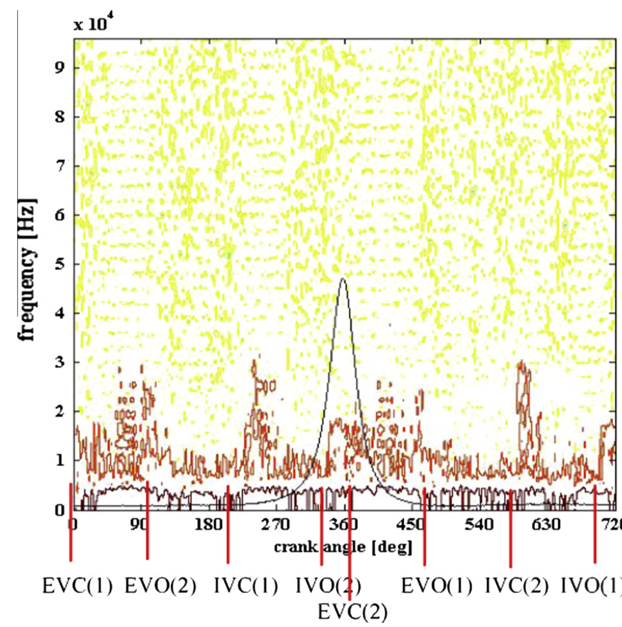

Fig. 11. Motored engine noise spectrogram, 2000 rpm; —— pressure-crank angle evolution.

the highest frequency components in the spectrogram. The frequencies below 40 kHz well represent the combustion process.

The analysis of the noise spectrograms related to a variation of injection parameters setting and to different engine speed/load values demonstrated no significant modifications as regards the results here shown.

Based on the frequency analysis of the signals, a frequency band was defined in which the contribution of the combustion process in the noise radiation was more evident. Such a band (2.5–40 kHz) was used to filter the acoustic signals in order to isolate the frequency components that are well correlated with the combustion process.

The following Fig. 12 shows some of the results, obtained for the condition of 2000 rpm, full load, injection setting according to mode 1 (all data were normalized by dividing for the respective maximum values).

The comparison between plot (a) and (b) highlights that the chosen frequency band was properly defined, since in the filtered microphone trace only the components mainly caused by the combustion processes are noticeable.

Similar results were obtained for the other signals acquired in the entire engine operative field.

4.2. Combustion diagnosis via noise indicators

In order to realize a control system that uses the acoustic radiation for monitoring the combustion process effectiveness, the

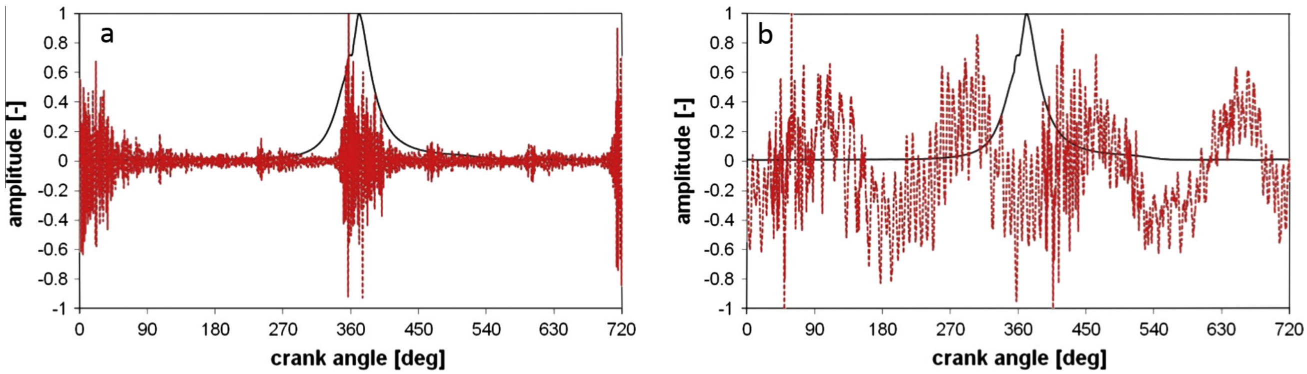

Fig. 12. (a) —— In-cylinder pressure and ······ filtered noise emission; (b) —— in-cylinder pressure and ······ noise emission at 2000 rpm, full load, mode 1.

acquired signals were analyzed aimed at identifying indices able to correlate combustion noise and combustion quality.

In the first section of this paragraph, the indices for combustion development characterization are defined; the second section is devoted to define the indices able to characterize the engine noise emission. Results are presented in the third section, with the aim of demonstrating that these indices may be used in a control algorithm as combustion performance feedback variables. An algorithm may thus be implemented in which the estimation of the combustion parameters is performed by using only the engine radiation measurement as input.

For what concerns the in-cylinder pressure development during the combustion process:

– combustion index, CI: it was computed as the sum of the third octave band level of the in-cylinder pressure in the 315–3150 Hz

$$CI = 10\log\left(10^{L_p(315)/10} + 10^{L_p(400)/10} + \ldots\ldots + 10^{L_p(3150)/10}\right) \quad (1)$$

– crank angle degree of 50% and 100% mass burned, MBF50 and MBF100, respectively. These indices are key parameters to obtain information of combustion phasing. They were computed starting from the rate of heat release, ROHR, that was evaluated through equation

$$\frac{dQ}{d\alpha} = \frac{1}{\gamma - 1} V \frac{dP_c}{d\alpha} + \frac{\gamma}{\gamma - 1} P_c \frac{dV}{d\alpha} + \frac{dQ_r}{d\alpha} \quad (2)$$

(where γ is the specific heat ratio, α is the crank-angle, P_c is the in-cylinder pressure and V is the in-cylinder volume. The third term on the right end side indicates the instantaneous heat loss to the cylinder wall that was computed by the Woschni model).

Once the ROHR was computed, the cumulated heat release (CHR) was evaluated and then normalized with respect to the maximum values, thus allowing to compute MBF50 and MBF100.

– maximum pressure rise rate, MPRR: it was defined as the peak rate of pressure rise during the combustion phase.

The definition of such indices was based on the need to find indicators able to sense the combustion development; other indicators may be found in literature, defined with the main objective of estimating the engine noise from cylinder pressure data in lieu of microphone data [19,28].

For what concerns the noise radiation, the following indices were defined:

– start of combustion noise, SCN: it corresponds to the crank angle value in which the combustion emission is equal to 0.5 Pa (Fig. 13);

– end of combustion noise, ECN: it corresponds to the crank angle value at which the combustion emission is lower than 0.5 Pa for at least 10 deg CA of the crankshaft (Fig. 13);

– noise index, NI: it was defined as the engine noise filtered in the frequency band 0.25–40 kHz, in which the radiated combustion energy was concentrated.

These indices were computed in the complete engine operative field and for a variation of the injection parameters setting.

The attention was then aimed at assessing the existence of a relation between noise emission and combustion development indices, to be used in an algorithm in which the combustion progress is evaluated only based on the engine radiated noise. For what concerns the engine radiation, it was found a connection between the crank angle values corresponding to the start of combustion noise (SCN) and the beginning of injection process (SOI_{pre}). A relation between the crank angle degree corresponding to the end of combustion noise (ECN) and the indicator of fuel burning completion (MBF100) was found. Furthermore, a dependence of the noise index (that represents an evaluation of the noise contribution due to combustion source) to MBF50 was identified and a relationship between NI and the combustion index (that represents an evaluation of the pressure components in the frequency band that is mainly affected by the combustion process) was found. In the following figures the obtained results are presented and discussed.

In Fig. 14, the relation between the crank angle degrees of start of combustion (SCN) and start of pre-injection (SOI_{pre}) is highlighted. Fig. 15 shows the crank angle degrees corresponding to the end of combustion (ECN) versus the crank angle degrees of 100% burned mass (MBF100).

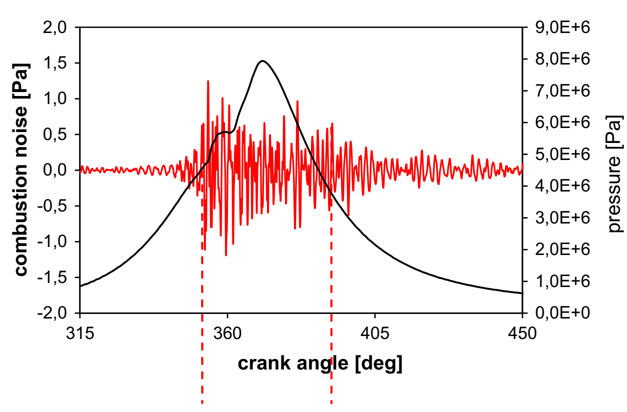

Fig. 13. Combustion related noise emission and indices definition.

In each figure, three groups of data are depicted; each one is related to a different value of engine speed (i.e. 2000, 3000 and 3600 rpm). For each engine speed value, 8 points are shown (corresponding to mode 1, load values 50%, 60%, 80% and 100%, and modes from 2 to 4, 100% load) in order to highlight the effect of a variation of load value and injection strategy. SOI_{pre} and SCN are expressed in terms of crank angle degrees BTDC.

The interpolation lines and the coefficient of correlations, *R*, are also shown (when the value of *R* is equal to 1, an absolute correlation is implied). It is possible to observe the high value of *R*, thus indicating the good correlation among the data related to each value of the engine speed. It was observed that the maximum error occurs for data acquired at high values of the engine speed: as the engine speed increases, the energy of the mechanical source also increases. Therefore, it is more difficult to discriminate between those components and those related to the combustion process. The high correlation among the data suggests the worthwhile employment of the noise indicators (SCN and ECN) to evaluate the crank angle period in which the combustion process takes place.

The relation between MPRR and engine noise index was investigated, since in the literature, the maximum pressure rise rate during combustion is used as a measure of combustion noise [20,28]. In Fig. 16, the noise index trend versus MPRR is shown. The data have been acquired during tests at 2000, 3000 and 3600 rpm: mode 1 (load values 50%, 60%, 80% and 100%) and modes from 2 to 4 (100% load). It is possible to observe the low correlation of the noise index with the maximum rate of pressure increase data for 3000 and 3600 rpm; concerning the data related to the lower value of the engine speed, 2000 rpm, the absence of any type of relationship among the data may be noted. This behavior agrees with the results obtained by [25] and may be justified by considering the small crank angle interval to which it is related in comparison to that one in which NI level was computed.

Fig. 17 presents the variation of NI with the crank angle at which 50% of mass is burned (MBF50). The data are characterized by a general good correlation, even though high scattering affects some data related to 3000 rpm. Nevertheless, the relationship that characterizes all the obtained trends highlights the possible employment of the noise index to evaluate the crank angle value corresponding to 50% of the combustion development.

Fig. 18 presents a plot highlighting the correlation between combustion and noise indices levels.

The points are grouped into 3 series, based on the engine speed value (2000, 3000 and 3600 rpm). For each engine speed value, the data correspond to a variation of load condition and of injection strategy (according to previous figures). In the plot, the interpolation straight lines are also drawn, in order to highlight the linear correlation among the data.

A variation of the injected mass quantity or of the injection strategy is responsible for a variation of the combustion develop-

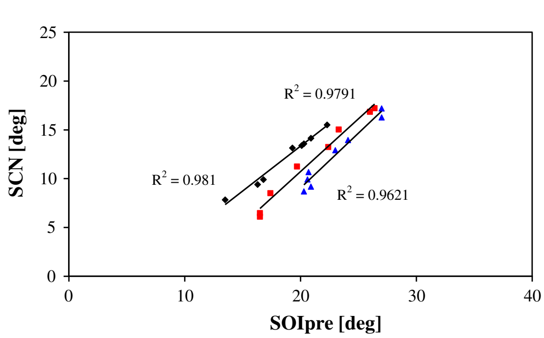

Fig. 14. Start of combustion noise versus SOI_{pre}: ♦ 2000 rpm, ■ 3000 rpm, ▲ 3600 rpm.

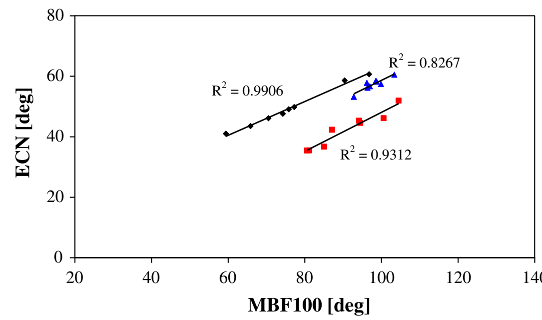

Fig. 15. End of combustion noise versus 100% of burned mass: ♦ 2000 rpm, ■ 3000 rpm, ▲ 3600 rpm.

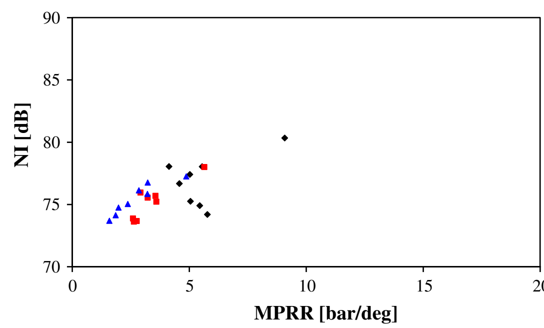

Fig. 16. Noise index trend versus maximum pressure rise rate: ♦ 2000 rpm, ■ 3000 rpm, ▲ 3600 rpm.

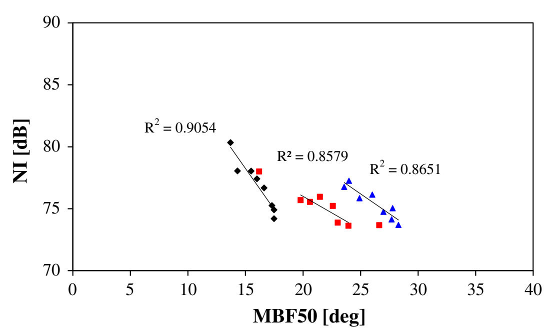

Fig. 17. Noise index versus 50% of burned mass: ♦ 2000 rpm, ■ 3000 rpm, ▲ 3600 rpm.

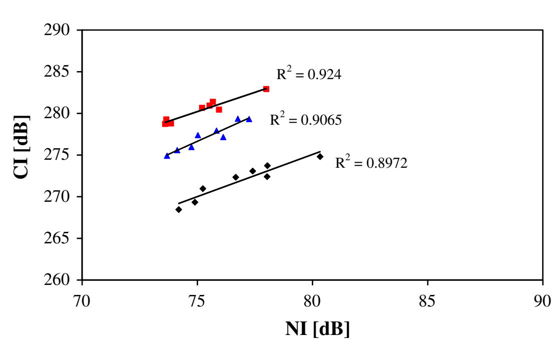

Fig. 18. Combustion and noise indices trends: ♦ 2000 rpm, ■ 3000 rpm, ▲ 3600 rpm.

ment, and therefore of the combustion index, CI. Such a variation corresponds to a linear change of the noise index, NI, that represents the contribution of the combustion process to the noise radiation. Based on the good agreement between the indices, it can be

Table 4
Linear interpolation coefficients.

	Linear correlation coefficients	
	a	*b*
2000 rpm	1.0143	193.93
3000 rpm	0.926	210.76
3600 rpm	1.2496	182.92

Table 5
Relationship between combustion and noise indices.

Relationship between combustion and noise indices			
Mode	SCN	ECN	NI
SOI_{pre}	X		
MBF50			X
MBF100		X	
MPRR			
CI			X

assessed that the frequency band used to define the CI level was properly selected. The accuracy of the recorded acoustic emission (NI) in predicting the CI level allows to express the correlation between CI and NI by means of the following expression:

$$CI = a\,NI + b \tag{3}$$

The coefficients a and b have been identified; the obtained values are related to the engine speed value and are reported in Table 4.

The following Table 5 summarizes the obtained results: in the columns, noise radiation indices are reported, whereas in the lines, the indicators for the injection and combustion process are shown. Cross symbols are used to highlight that a relationship between the data was established.

5. Conclusion

This paper investigates the use of microphones for combustion control and diagnosis applications. The research work arises from the observation that the engine noise emission contains useful information about the combustion process.

Since different sources contribute to the engine radiation, the attention was devoted to analyze the relation between in-cylinder pressure and acoustic signals and to extract the noise components mainly caused by the combustion process.

Tests in the entire engine operative field have demonstrated that:

- the injection process and the combustion performance are related to the engine noise emission;
- high values of correlation coefficients exist between the indices for combustion development (CI, MBF50, MBF100) and injection process (SOI) characterization and indices for noise radiation evaluation (SCN, ECN, NI).

Basing on these findings, a closed-loop algorithm could be integrated in the ECU, in which the real time processing of acoustic data could be performed and the combustion properties could be evaluated only by using the engine radiation measurement as input. This information could be then compared to target values and new injection parameter values imposed on the engine in order to guarantee performance requirements in terms of available torque, pollutants emission and sound quality issues.

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