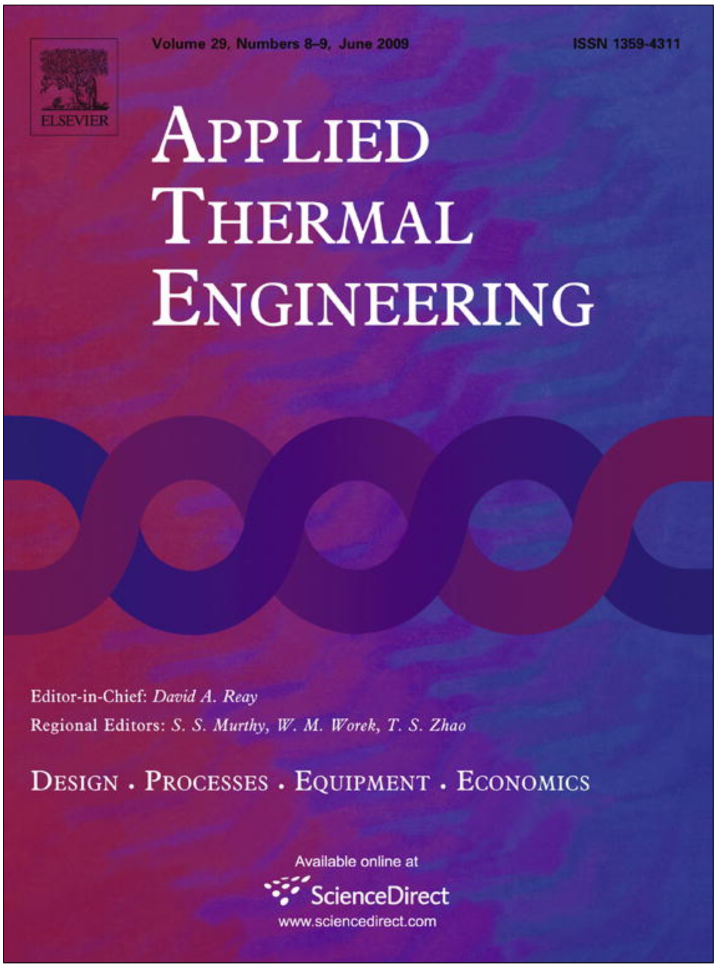
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Diagnosis of internal combustion engine through vibration and acoustic pressure non-intrusive measurements

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A B S T R A C T

The present study proposes a diagnosis methodology for internal combustion engines (I.C.E.) working conditions, by means of non-invasive measurements on the cylinder head, such as acoustic and vibration, related to the internal indicated mean effective pressure. The experimental campaign was carried out on the internal combustion engine of the cogeneration plant at the Faculty of Engineering – University of Perugia (Italy), for different values of the engine load. Results show that both the vibration and acoustic signals measured on the cylinder head are strictly related to the phenomena inside the cylinder, depending on the engine load and the combustion frequency. Some vibration and acoustic indexes were introduced, in order to evaluate the working regimen of the engine. Their values, obtained for different engine loads, constitute the reference values; when the methodology was implemented, the evaluation of such indexes allows to estimate the combustion quality, comparing measured and reference values.

1. Introduction

The condition monitoring of diesel engines has been the aim of many research approaches. Most of them are based on the acquisition of signals, which can be the cylinder pressure, the engine vibration, the crankshaft acceleration. The processing of the acquired signals and the comparison with threshold values allows to discriminate between regular and faulty engine running condition [1].

Among these approaches, vibration and acoustic measurements offer a great potential due over all to the non-intrusive nature of the measurements. The sound generation of a diesel engine can be modelled based upon the combustion process, and time-frequency analysis can be used to reveal the underlying characteristics of the sound waves [2,3].

The aim of the present paper is to develop a diagnosis methodology for internal combustion engines (I.C.E.) quality, by evaluating macroscopic working parameters measured with non-invasive instruments [4]. The study was carried out considering the internal combustion engine of the cogeneration plant at the Faculty of Engineering – University of Perugia (Italy).

Measurements were carried out considering both Caterpillar CAT G3516 LETA, working until September 2004, and a new unit, CAT G3516B, substituting the former due to serious failure.

The diagnosis methodology is based on the characterization of the working conditions by means of acoustics and vibrations measurements and relating data to the indicated mean effective pressure inside the cylinder. Some indexes were introduced, in order to evaluate the working regimen of the engine. The mean indicated cycle and the intake and exhaust valve lift law of CAT G3516 LETA for different values of the produced electric power were related to the vibration measurements on the cylinder head and, for CAT G3516B, to the acoustic pressure levels in a close-frequency band. Some parameters were proposed, in order to relate data to the indicated mean effective pressure in the monitored cylinder, which indicates the working state of the engine. A reliable methodology to evaluate the internal combustion engines quality was finally developed.

2. The Faculty of Engineering cogeneration plant – University of Perugia

The experimental activity was carried out on the I.C.E. of the cogeneration plant installed at the Faculty of Engineering (University of Perugia, Italy).

Measurements were carried out both on the Caterpillar CAT G3516 LETA Engine and the new unit, CAT G3516B LE, installed for substituting the first one for serious failure.

Both engines CAT G3516B LE and CAT G3516 LETA have 16 cylinders V disposed and are characterized by constant low rotation velocity (1500 rpm), natural gas fuelling, controlled ignition, turbocharging with aftercooling. The main characteristics of both engines are listed in Table 1.

A heat recovery, both in winter and summer, is carried out for the Faculty air conditioning plant; heat is recovered at high

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Table 1
Mean CAT G3516B and CAT G3516 LETA technical data relative to standard conditions and after coolerwater inlet temperature of 25 °C

	CAT G3516B	CAT G3516 LETA
Fuel	Natural gas	Natural gas
Burning	Lean burn	Lean burn
Velocity rotation (rpm)	1500	1500
Cylinders	*V* – 16	*V* – 16
Bore (mm)	170	170
Stroke (mm)	190	190
Compression ratio	11.7:1	11:1
Number of valves in the cylinder	4	4
Sweft volume (cm^3)	69,000	69,000
Shaft power (kW)	1130	1030
Feeding pressure	10 kPa	Intake manifold pressure = 50 mbar
Inlet temperature of the aftercooler water	54 °C	Aftercooler output temperature = 32 °C
Outlet temperature of the aftercooler water (°C)	99	98
Ignition system	Electronic	Electronic
Emission level	Low emission	Low emission
Standard specific consumption	925 MJ/kWh	9.96 kJ/kWh
Standard efficiency (%)	37.40	36.10

(exhaust gases) and low (engine cooling) temperature. In summer the recovered heat is employed in a water–lithium bromide absorption chiller (thermal power 2 MW_t). The electric energy, produced by the engine working at a constant load of 950 kW (just a little below than the maximum value), is used to satisfy the Faculty demand. The exceeding part is sold to the National Electric Grid, while electric energy is taken when the engine is not working. The electric energy exchange is regulated by means of suitable contracts.

Fig. 1 shows a scheme of the plant: the three-way valve (5) sets the water flow rate for the engine cooling and the parallel auxiliary circuit, according to the temperature of the engine cooling fluid; if higher than 85 °C, part of the flow rate is sent to the auxiliary heat exchanger (1) where it is cooled by the water from the evaporative tower (2). The on–off three-way servocontrol valve (9) sends gases from the turbocharging turbines directly to the exhaust and to the high temperature shell and tube heat exchanger (8), in order to guarantee the temperature variation of the hot water.

In the scheme of Fig. 1 the auxiliary chillers and boilers, utilized in the case of heat recovering not present or insufficient, are not indicated. Also the flow rate circulating in winter conditions for the user is not present; it is controlled by a three-way valve proportional to the water temperature at delivery.

3. Indicated cycle survey as a function of engine operation regime and main parameters evaluation

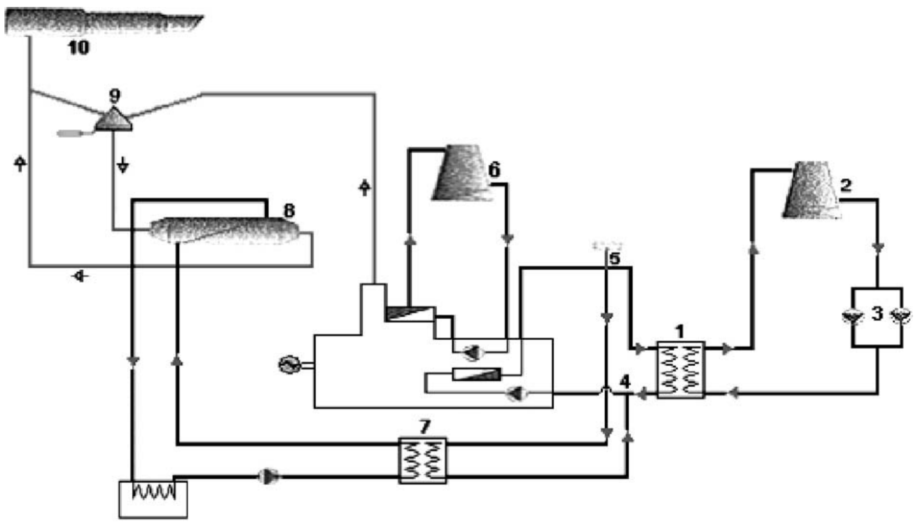
3.1. Instrumentation and measurement methodology

The engine indicated cycle represents the thermodynamic cycle followed by a working fluid in the engine combustion chamber; it could be experimentally obtained using a pressure sensor pointed out in the combustion chamber.

The preliminary work involved an experimental acquisition of the intake and exhaust valves lift law. To this aim, taking as reference the fly-wheel at the engine head, it was possible to relate the lift of the intake and exhaust valves to the crankshaft angle. Fig. 2 shows the obtained cams profiles on CAT G3516 LETA engine.

The employed equipment was composed by:

- Tektronix TDS 420 A oscilloscope;
- magnetic pick-up;
- Kistler Type 6055BB Pressure sensor (piezoelectric sensor, sensitivity 20 pC/bar, maximum measurement temperature 400 °C), characterized by an accuracy <= ±0.5% of the full scale value and a calibrated range of 0–100 bar.



1 = 7 = heat exchanger, 2 = 6 = evaporative tower, 3 = pumps; 4 = T joint, 5 = three-way valve, 8 = shell and tube heat exchanger, 9 = servocontrol valve , 10 = exhaust

Fig. 1. Cogeneration plant layout.

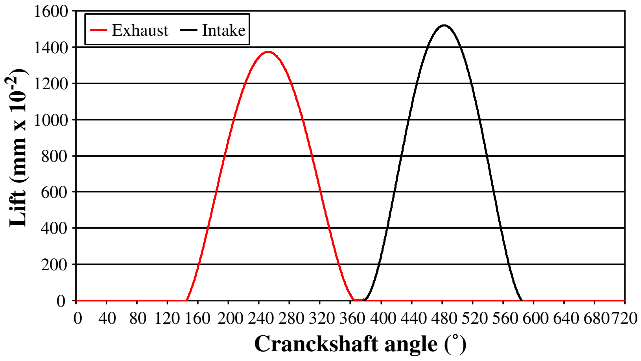


Fig. 2. CAT G3516 LETA: lift law of the intake and exhaust valves.

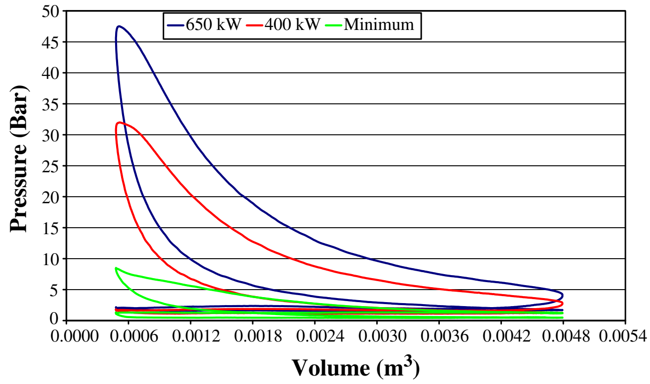


Fig. 3. CAT G3516 LETA: mean indicated cycle at different engine loads.

The pressure sensor was placed in correspondence of the monitored cylinder top dead centre (TDC); a magnetic pick-up was positioned on the damped wheel even in correspondence of the TDC, in order to associate to each pressure value measurement the corresponding crank angle value (and also the value of the combustion chamber volume). Moreover, a further pick-up was placed in correspondence of the fly-wheel at the engine head.

Signals surveyed from the two magnetic picks-up and from the pressure sensor were acquired by the oscilloscope, with a 25 kHz sampling frequency and a wave shape of 30,000 points, corresponding to a total sampling time of 1.2 s.

Tests were carried out on CAT G3516 LETA in three different load settings:

- 650 kW;
- 450 kW;
- without load (min).

3.2. Measurements results

Considering 1500 rpm speed engine and a sampling time of 1.2 s, 15 engine cycles and consequently 30 passages to the TDC were acquired.

The pressure sensor takes the pressure difference, so measured data must be corrected considering the absolute pressure relative to the engine inlet manifold. This value (Table 2, column 2) was acquired for all the different load settings of the test, using the Caterpillar DDT diagnostic module, that allows to read the engine pressure sensor placed on the inlet manifold.

The indicated cycle describes the pressure variation inside the combustion chamber as a function of the variation of the chamber volume; therefore the pressure trend must be related to the combustion chamber volume as a function of the crankshaft angle, by means of the following equation [5].

$$V = V_c\left\{\frac{1}{r-1} + \frac{1}{2}\left[1 + \frac{1}{\Lambda} - \cos\theta - \frac{1}{\Lambda}\sqrt{1-\Lambda^2\sin^2\theta}\right]\right\} \qquad (1)$$

Table 2
Absolute pressure values in the engine inlet manifold and IMEP values as a load function

Load (kW)	Absolute pressure (kPa)	IMEP (bar)
650	157	9.761256
400	111	6.406263
Lowest	40–48	1.094755

where

- V_c is the unitary displacement;
- r is the compression ratio;
- Λ is the ratio between connecting rod length and crank radius;
- θ is the crankshaft angle.

The mean indicated cycle relative to the tested load settings was evaluated according to the described methodology; results are illustrated in Fig. 3.

The indicated mean effective pressure (IMEP) is the pressure value applied constantly on the pistons during the only expansion phase; it yields the work produced by a complete engine cycle.

The IMEP could be consequently calculated as the ratio between the indicated work produced per mean indicated cycle and the displacement [5]:

$$\mathrm{IMEP} = \frac{W_i}{V_{tot}} \qquad (2)$$

where

- V_{tot} is the total displacement;
- W_i is the indicated work produced per engine cycle.

The indicated work associated to one cylinder could be calculated starting from the mean indicated cycle by integrating the infinitesimal work in all the cycle. In Table 2, column 3, the IMEP values are summarized at the load variation.

4. Measurement of the cylinder head vibration conditions, varying engine operation regime

4.1. Instrumentation and measurement methodology

The correlation between vibration measurements acquired by an accelerometer placed on the cylinders head and engine fundamental parameters, such as cam profiles and inside cylinder pressure, is interesting to analyze the operational condition of internal combustion engine for diagnostic purposes.

To such aim, the necessary data were acquired at the same time. In particular vibration measurements were carried out by employing PCB Piezotronics 353B17 accelerometers (sensitivity 1.02 mV, measurement step ±4905 m/s^2 pk) and a signal conditioner PCB 442C04, as showed in Fig. 4.

Accelerometers were placed at 4 points on engine head upper surface; inside the same cylinder the indicated cycle was acquired. Vibration measurements, carried out following the same sampling parameters previously described, were performed on CAT G3516

Fig. 4. Vibration and acoustic signal acquisition on the cylinder No. 9 of the CAT G3516B engine.

LETA engine in correspondence of three load settings: 650 kW, 450 kW, minimum load and on engine CAT G3516B at 950 kW.

4.2. Results of measurements. Definition and evaluation of characteristic indices

Fig. 5 shows the vibration signal state as a function of the crankshaft angle, varying load conditions.

Superimposing the vibration signals obtained from CAT G3516 LETA for the three load settings, it can be noted that they are strongly related to the operation engine and in particular to the inside cylinder pressure. In fact there are greater vibration signal peaks as load increases.

Then it can be asserted that vibration signal acquired on the engine cylinder head is a good indicator of the combustion phenomena being in an I.C.E., and in particular of the pressure signal characteristic of the indicated cycle at the different loads.

Subsequently the acquired vibration signals were elaborated in frequency through the Fourier discrete transform, DFT (Fig. 6). The amplitude value trend (expressed in Volt RMS), at the frequency variation, strongly decreases with increase in frequency; in the three load settings the most part of signal energy is in the frequency range within 2000 Hz, to confirm that mechanical solicitations, that occur mostly at low frequencies, represent the main part of the force globally transmitted at the cylinder head.

Fig. 7 shows DFT of vibration signal acquired on CAT G3516 LETA; it can be noted that the signal presents a fundamental frequency at 12.5 Hz, corresponding to the combustion frequency.

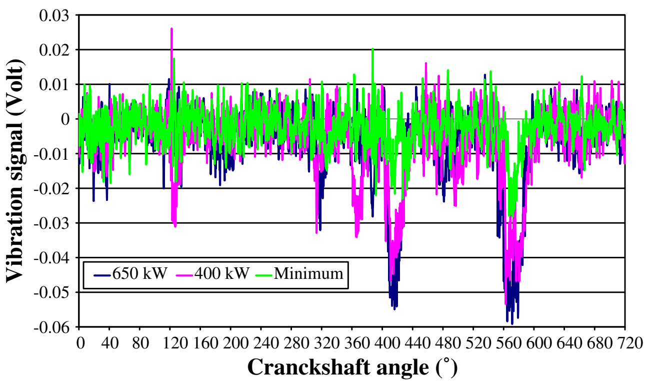


Fig. 5. Vibration signal state in function of the crankshaft angle with engine load variation.

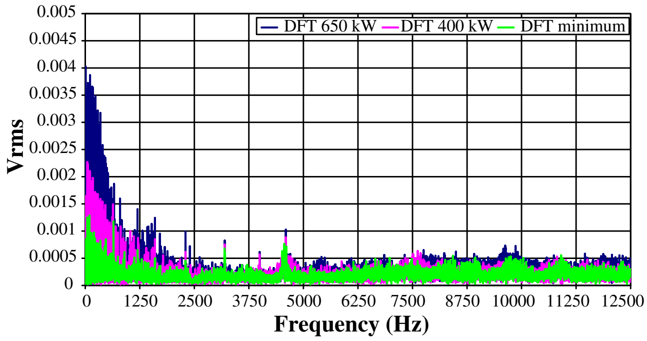


Fig. 6. DFT of the vibration signal.

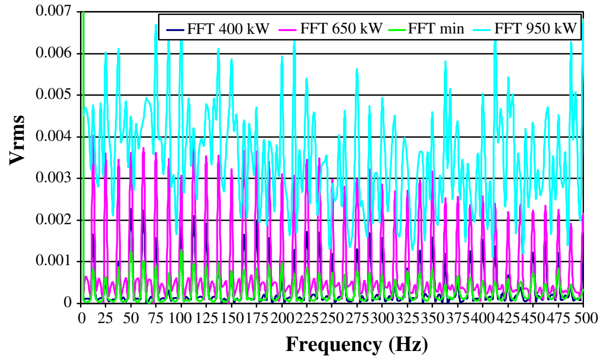


Fig. 7. Comparison between the cylinder head state of vibration (in the frequency domain) of CAT G3516 LETA and CAT G3516B.

Vibration measurements on Caterpillar CAT G3516B were executed only at 950 kW load.

The agreement between cylinder head state of vibration of CAT G3516 LETA and G3516B engine is shown in Fig. 7, where the vibration signal is plotted in the frequency domain. The comparison of the DFT trend of the cylinder head vibration signal between CAT G3516 LETA and CAT G3516B shows load influences on the vibration transmitted to the structure; vibration value measured on the new engine at the load of 950 kW is constantly higher than the value measured on the I.C.E. previously installed.

It is therefore suitable to find vibration signal characteristic parameters; with such aim in mind the RMS value, or vibration effective value, supplies a good indication of its intensity [5], in fact:

$$q_i(t)_{RMS} = \sqrt{\overline{q_i^2(t)}} \tag{3}$$

with $q_{i(}t)$ vibration instantaneous value.

Table 3, column 2, summarizes the RMS values at the load variation for the CAT G3516 LETA engine and at the load of 950 kW for CAT G3516B.

The RMS value of the signal noticed on CAT G3516B engine is equal to 0.055 V, approximately four times higher than the value calculated for the old engine CAT G3516 LETA at 650 kW, and it confirms what previously stated.

Then, to correlate the IMEP to the vibration signal in frequency domain acquired on the engine cylinder head, attention was focused on the definition of a suitable indicator; the best result, as reported in the next paragraph, was obtained by employing an indicator named I_{fv}. Such indicator is defined as the mean of the frequency peaks relative to the first hundred harmonics of the fundamental frequency; the choice of considering only those

Table 3
Vibration RMS values and I_{fv} index as a load function related to CAT G3516 LETA and CAT G3516B engine

	Load (kW)	RMS (V)	I_{fv} (V)
CAT G3516 LETA	650	0.013645	0.001801
	400	0.012093	0.000907
	Lowest	0.006403	0.000488
CAT G3516B	950	0.055000	0.004570

harmonics is justified by the characteristic of the signal, that quickly decreases in amplitude over 1500 Hz.

In Table 3, column 3, the I_{fv} values for CAT G3516 LETA and CAT G3516B are shown.

The parameter suitability and all hypotheses previously assumed are demonstrated for CAT G3516B operating at 950 kW by a value higher than the one relative to CAT G3516 LETA at the load of 650 kW.

This parameter verifies once again the correlation between inside cylinder pressure and vibration acquired on the cylinder head, and allows to link results obtained for CAT G3516 LETA engine with CAT G3516B.

5. Acoustic pressure level observation near a cylinder

5.1. Experimental apparatus and measurement methodology

Acoustic pressure measurements were carried out near the investigated cylinder, in order to obtain an acoustic characterization of the combustion inside it [6–8].

The experimental apparatus was constituted by:

- a spectrum analyzer Symphonie, by 01 dB – Stell: it answers to precision class 1 according to IEC 651 and IEC 804, digital filters (class 0) are in compliance with IEC 1260; dynamic range 20–135 dB; weighting A, B, C and Lin;
- a 1/2″ random incidence microphone by G.R.A.S. (sound and vibration): it complies with the requirements in IEC 1094 part 4; nominal open circuit sensitivity at 250 Hz 50 mV/Pa; frequency response ±2 dB (3.15–12.5 kHz), ±1 dB (12.5–8 kHz); upper limit of dynamic range 148 dB (Ref. 20 μPa), lower limit of dynamic range 16 dBA (Ref. 20 μPa);
- a 1/2″ condenser preamplificator (PRE12H) by 01 dB – Stell: frequency scale 1–20 kHz, gain, typical −0.035 dB, max −0.050 dB; noise measured with 15 pF equivalent capacity: weighted A typical 2.5 μV, linear 22–22 kHz typical 10 μV;
- a CAL 01 calibrator, by 01 dB – Stell: according to IEC 942; typical sound pressure level 74, 94, 114 dB; stability of sound pressure level ±0.1 dB; acoustic pressure tolerance ±0.3 dB; frequency 1 kHz ±20 Hz; stability of frequency >0.5%.

The acoustic signal was recorded for a period of 30 s in the frequency range 0–20 kHz and post-processed by means of a suitable software, dBFA32. The signal elaboration was made by a narrow-band analysis through a Hanning FFT with a 6.25 Hz step. Measurements were carried out on CAT G3516B engine in 950 and 650 kW load configuration.

5.2. Experimental results. Typical index definition and its evaluation

Fig. 8 shows the acoustic pressure trend in the frequency domain, for the load configuration of 950 and 650 kW. The measured acoustic pressure also depends on the load, values at 950 kW load are always higher than the ones at 650 kW. Such as in vibration

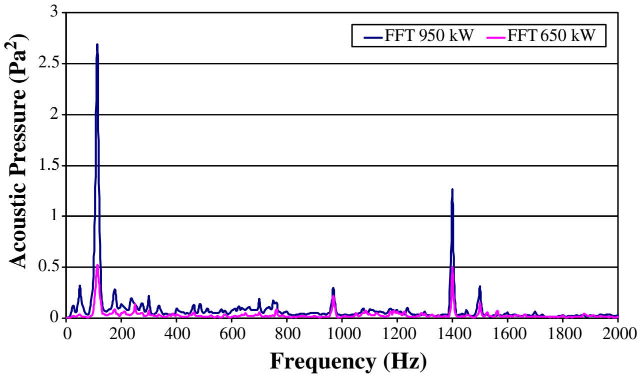


Fig. 8. Acoustic pressure trend in the frequency domain for the load configurations of 950 and 650 kW (CAT G3516B).

Table 4
CAT G3516B engine: index I_{fa}

Load (kW)	I_{fa} (Pa^2)
950	0.114283
650	0.038532

measurements, the signal peaks correspond to the combustion harmonic frequency (12.5 Hz). The very high value of the recorded signal at 950 kW near the 112.5 Hz frequency is probably caused by the room second resonance frequency (115 Hz) contribution, calculated according to the engine room dimensions.

In the frequency domain, for acoustic signal so as for the vibration one, the mean of the peaks related to the first 100 harmonics of the combustion basic frequency were evaluated; the index was named I_{fa} (Table 4).

6. Comparison between the experimental results and the proposed diagnostic methodology validation

6.1. Correlation between inside cylinder pressure (IMEP) and vibration cylinder state (RMS, I_{fv})

Fig. 9 shows the vibration trends recorded on the cylinder of CAT G3516 LETA engine and the valves lift law calculated with the methodology explained in the first paragraph; it is possible to remark that the valve opening and closing contribute to the vibration generation. The pressure variation in the intake duct at the moment of the valve opening, together with the impact due

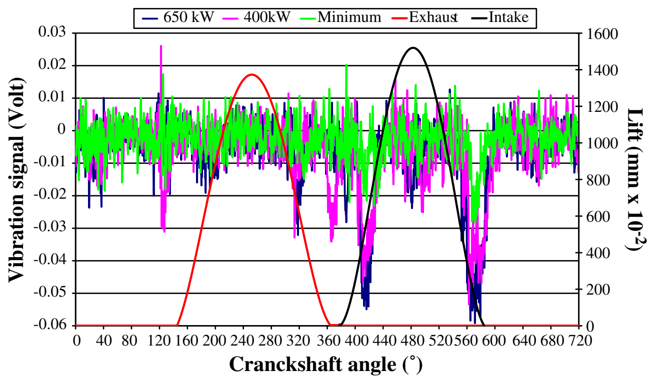


Fig. 9. Vibration trends recorded on the cylinder (CAT G3516 LETA engine) and valves lift law.

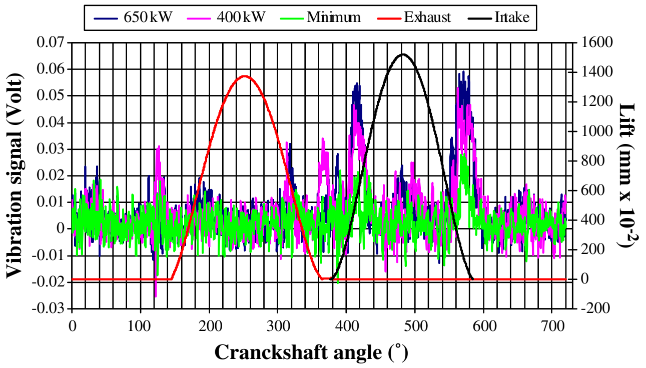


Fig. 10. Inverse value of the vibration signal recorded on the cylinder (CAT G3516 LETA engine) and valves lift law.

to the valve closing, contributes highly to the cylinder vibration. These vibrations are superimposed to the ones generated by the pressure variation due to combustion, so that the generated global signal depends only on the internal cylinder pressure. The variation on the vibration signal, recorded in correspondence of the valve opening and closing, is more evident if its inverse value is calculated, as shown in Fig. 10.

The recorded vibration signal was analyzed together with the measured pressure values on CAT G3516 LETA and the valves lift law trend through a 3D visualization of the DFT. The vibration signal spectrograph was obtained as a load function for the CAT G3516 LETA and CAT G3516B engine; the spectrograph is a DFT signal visualization as a function of the acquisition time. In this case an engine complete cycle was considered.

The DFT value is visualized through a chromatic scale and it is possible to analyze the DFT amplitude variation with frequency. For example, Fig. 11 shows the CAT G3516 LETA engine spectrograph at the 450 kW load (red corresponds to the signal amplitude peaks) together with the valves lift law; to calculate the DFT, a Hanning window with 56 samples width was considered.

Fig. 11 shows a correlation between the signal value in terms of its amplitude and the position of the valves, which cause a vibration peak at each opening and closing phase. Moreover the energy distribution is prevalent in low-frequency. From the values in Table 3 it is possible to note that both the characteristic parameters of the vibration signal (RMS, I_{fv}) depend on the I.C.E. load. Moreover comparable reductions of such parameters take place at the load decrement.

Finally, as remarked in the time signal analysis, also in the frequency domain there is a load dependence. In fact as the load increases, the DFT amplitude increases in correspondence of the

Table 5
Correlation between the IMEP and the RMS vibration values

Load (kW)	IMEP (bar)	Difference (%)	RMS (V)	Difference (%)	I_{fv} (V)	Difference (%)
650	0.013645	11	9.7612564	34	0.001801	50
400	0.012093	47	6.4062634	83	0.000907	46
Lowest	0.006403	–	1.0947554	–	0.000488	–

basic frequency and its harmonics. So the vibration phenomenon in the cylinder upper area is proportional to the internal pressure and it depends on the I.C.E. load. From the recorded values it is possible to obtain the cylinder internal pressure trend or, more easily, the correspondence IMEP using as input data the vibration intensity; this is possible because there is a correlation between the IMEP and the RMS vibration value, as shown in Table 5. In the time domain the signal analysis gives a good tool to evaluate, at a fixed load, the engine operation conditions and the combustion quality through the comparison between measured RMS values and the reference ones.

6.2. Correlation between the single cylinder vibrational state and the single cylinder pressure level

A comparison between vibration and acoustic power in the same frequency range was carried out in the 950 kW configuration load (Fig. 12). Values of I_f and of its percentage variation for CAT G3526B at 950 and 650 kW load, calculated for both vibration and pressure level, are reported in Table 6; the percentage variation has approximately the same values, due to a strict correlation between the two parameters.

Results show that the combustion quality could be evaluated without distinction from RMS, I_{fv} or I_{fa} values; they are in fact all related to the indicated mean effective pressure inside the cylinder.

6.3. Diagnostic methodology

Pressure or vibration signals could be employed without distinction to detect phenomena in the combustion chamber. If I_f, calculated from acoustic or vibration measurements, is not congruent with a correct engine functioning, an irregular combustion and a consequent anomalous value of the IMEP are possible.

This methodology could point out misfire and elastic band seal problems. Misfire, as an example, produces a shift of the fundamental frequency of the combustion, with a consequent lower value of the index, while if seal problems occur in a cylinder, the corresponding IMEP diminishes and with it also RMS and I_{fv} values.

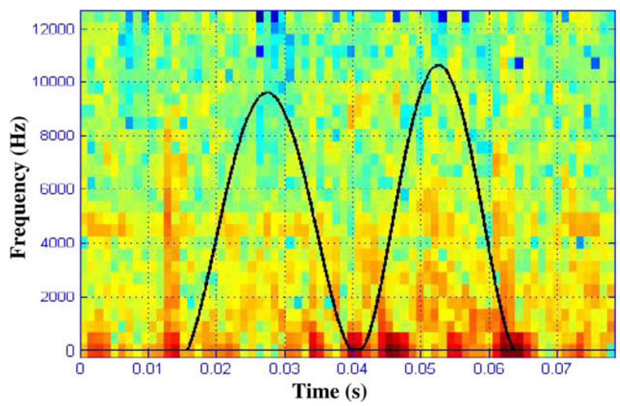


Fig. 11. CAT G3516 LETA spectrograph (400 kW) and valves lift law.

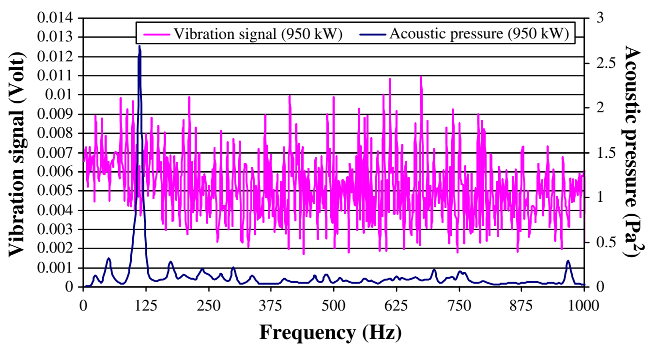


Fig. 12. Comparison between the vibration signal at 950 kW load and the corresponding acoustic pressure.

Table 6
CAT G3526B engine: I_{fv} and I_{fa} indices and percentage difference

Load (kW)	I_{fv} (V)	Difference (%)	I_{fa} (Pa^2)	Difference (%)
950	0.0045724	61	0.114283	66
650	0.0018010		0.038532	

7. Conclusions

Monitoring working conditions and combustion quality in an internal combustion engine often requires intrusive techniques. Therefore the study of alternative diagnosis methodologies is desirable; in the present research a non-intrusive methodology is proposed, based on vibration and pressure level measurements on the cylinder heads. Both signals are strictly related to the phenomena inside the cylinder, depending on the combustion frequency.

In the analyzed internal combustion engines, at a constant rotation velocity (1500 rpm), a strict correlation among these parameters and the indicated mean effective pressure inside the cylinder was found.

Both vibration and pressure level signals were characterized by the internal load of the cylinder and by the combustion frequency (12.5 Hz).

In order to develop a valid methodology based on these signals, a graphic analysis was carried out; it showed that the signals amplitude is maximum at frequencies lower than 2 kHz; this is therefore the useful range for the development of alternative diagnosis methodologies.

A new index was proposed, calculated as the mean value of the first 100 harmonics of the combustion frequency of both the vibration (I_{fv}) and the pressure level signal (I_{fa}), together with the RMS value of the vibration vs. time.

The proposed indexes, obtained for different values of the engine load, allow to evaluate the indicated mean effective pressure inside the cylinder and to estimate the combustion quality, comparing measured and reference values.

Vibration and acoustic pressure levels could be employed without distinction: in particular, if the I_f value (calculated indifferently from vibration or pressure level measurements) is not congruent with the reference one, the combustion inside the cylinder in which measurement is carried out could be irregular, with a consequent anomalous value of the IMEP inside the same cylinder; it could happen when misfire or elastic band seal problems occur.

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