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Energy Procedia 101 (2016) 677 – 684

Energy Procedia

71st Conference of the Italian Thermal Machines Engineering Association, ATI2016, 14-16 September 2016, Turin, Italy

Combustion and Intake/Exhaust Systems Diagnosis Based on Acoustic Emissions of a GDI TC Engine

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Abstract

Due to increasingly stringent emission regulations and the need for more efficient powertrains, engine control systems that have been developed during the recent years have become more and more sophisticated. Obtaining accurate information about the combustion process and about all the subsystems that compose the engine can be considered key to reach the maximum overall performance. Low-cost in-cylinder pressure and turbo speed sensors are being developed, but they still present long-term reliability issues, and represent a considerable part of the entire engine management system cost. Sound emissions represent an extremely rich information source about the operating conditions of all the subsystems that comprise the entire engine. The paper shows how it is possible to extract fundamental information regarding the combustion process (such as knock and misfire), turbo speed, and air path fault at the same time, by performing an appropriate analysis of the engine acoustic emissions acquired from the very same microphone, which can thus be considered as an innovative, multifunction, and low-cost sensor for automotive applications.

Peer-review under responsibility of the Scientific Committee of ATI 2016.

Keywords: Acoustic emissions; combustion control; engine diagnosis; misfire; knock.

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Peer-review under responsibility of the Scientific Committee of ATI 2016.
doi:10.1016/j.egypro.2016.11.086

1. Introduction

In the recent years an increasing number of downsized, turbocharged and direct injection gasoline engines has been launched onto the market. The adoption of the downsizing concept leads to shift the average engine operating conditions toward higher efficiency points, while turbocharger systems enable higher torque to be reached, especially at lower engine speeds. This design concept has been proven as one of the possible solutions to meet the most recent emissions and fuel consumption regulations. Powerful and extremely complex engine control units (ECU) have recently been developed to manage such challenging and sophisticated engine systems.

Performing an accurate monitoring of the overall engine subsystems enables maximum efficiency and higher reliability to be reached. Knock is one of the main factors that prevent maximum combustion efficiency to be achieved for downsized, turbocharged gasoline engines [1,2]. Accelerometers are widely used for knock detection in mass production passenger cars instead of cylinder pressure sensors, for their well-known cost and reliability issues [3-6], and more recently also in-cylinder ion current sensing systems have been developed for the same purpose [7-9]. In the last years, turbocharger rotational speed sensors have been installed in heavy-duty applications and in some passenger cars, but they still represent an important rate of the overall engine management system cost. The on-board measurement of the compressor speed could allow the improvement of the performance of the boost controller, and it also allows using smaller safety factors (with respect to maximum rotational speed) then the ones typically needed to take into account the relatively large part-to-part variability that still affects turbocharger production lines. Indirect techniques to perform this measurement have been recently developed and can be found in scientific literature [10-12].

Another field that is crucial for optimal engine operation (and for complying with the most recent regulations) is the ability to correctly diagnose engine faults, such as, for example, missing combustions (or “misfires”) or intake/exhaust systems that present leakages. Several approaches have been proposed in the literature especially for misfire diagnosis [13,14], while the ability to detect even very small leaks in the intake or exhaust manifolds is still considered particularly challenging.

The paper shows the methodology that has been developed, and the results that have been achieved in a test bench, to extract from the engine acoustic emission crucial information related both to engine control (knock intensity and turbocharger rotational speed) and diagnosis (misfire and air/exhaust gas path fault).

2. Experimental Setup

The engine used for this study is a 4 cylinder 1.4L turbocharged direct injection engine, for passenger car applications. Its technical data are summarized in Table 1.

During the experiments, carried out on a test bench, the in-cylinder pressure of each cylinder has been measured by means of Kistler 6052A piezoelectric sensors. For the acoustic emission analysis, a microphone-based sensing device, developed by Magneti Marelli and known as Smart Acoustic Sensor (SAS), has been used. For all tests, the SAS has been placed on the intake side of the engine, under the intake manifold (fig.1). In-cylinder pressure and acoustic emission signals have been acquired simultaneously at 200 kHz by means of an On-Board Indicating analysis system (OBI-M2) by Alma Automotive [15]. Finally, a turbospeed DZ135 sensor (by MICRO-EPSILON [16]), facing to the compressor blades of the turbocharger, has been used to directly measure its rotational speed.

Knock has been externally induced by applying controlled spark advance increments, while turbocharger speed profiles have been performed by controlling the waste gate opening rate.

From a diagnostic point of view, misfire has been induced by controlled injection cut-off in each cylinder, under steady state condition, whereas holes of different diameter have been introduced in the intake plenum for air path fault detection analysis.

Table 1. Technical data of the engine used during the experimental tests.

Displacement	1390 cm^3
Stroke	75.6 mm
Bore	76.5 mm
Compression ratio	10:1
Max torque	220 Nm @ 1500-4000rpm
Max power	103 kW @ 6000 rpm
Intake system	Super and turbo charger

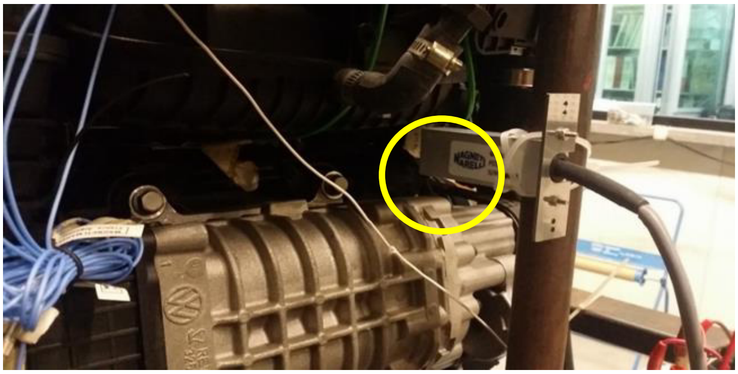

Fig. 1 Positioning of the Smart Acoustic Sensor.

3. Knock detection

The combustion chamber can be considered as a circular elastic membrane. When knock occurs, the fresh mixture in the peripheral zones of the combustion chamber auto-ignites and its extremely rapid combustion generates pressure waves that excite the combustion chamber natural frequencies. The natural modes of the combustion chamber are strictly related to the its geometrical dimensions and to the gas thermal state [17,18,19], and can be calculated by using Equation (1):

$$fr = C_s \frac{\rho(r,c)}{\pi B} \tag{1}$$

Where:
fr: resonant frequency, C_s: *speed of sound, B:* cylinder bore, ρ: wave number.

For the engine taken into account in this study, the main natural frequencies are summarized in Table 2.

Table 2. Engine combustion chamber natural frequencies.

r,c	ρ (r,c)	Fr [kHz]
0,1	3.82	15.93
0,2	7.01	29.23
1,0	1.841	7.68
1,2	5.33	22.23
1,3	8.53	35.57
2,0	3	12.51
2,2	6.75	28.15
3,0	4.2	17.52

Performing frequency analysis by means of a Fast Fourier Transformation (FFT) over pressure traces of knocking cycles shows that the frequencies identified by equation 1 are in fact particularly excited (fig.2(a)).

Knocking combustions are characterized by a characteristic sound that can be perceived by the human ear as a clink. Performing the same frequency analysis on the acoustic emissions confirms that knocking combustions tend to excite the same frequencies identified on the pressure signal. Figure 2(b) shows the results of FFT performed on the acoustic emissions of the very same cycles that have been shown in fig. 2(a).

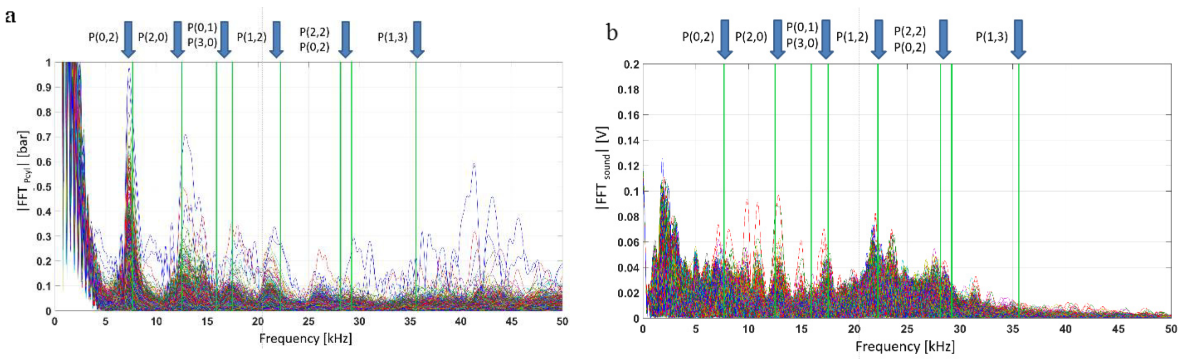

Fig. 2. Frequency analysis of (a) in-cylinder pressure (b) acoustic emissions in knock cycles

Given this observation, it may be possibly assumed that the knock sound emissions are emitted from the pressure waves that are generated inside the combustion chamber.

In the audio spectrum it may be noted that the signal energy spreads across a wide frequency range, that is due to the fact that the acoustic signal collects information related to all sound sources around the microphone.

Based on these considerations, knock detection via acoustic emissions should be performed through an analysis of the frequency bands close to combustion chamber natural modes, in order to avoid the influence of the surrounding environment. The Integral Sum of Divided Band Pass (SDBP) has therefore been chosen as the most appropriate knock index, because it allows isolating the frequency bands more sensitive to knock phenomena within the sound emissions. The mathematical structure of the index is shown in equation (2), six chamber natural frequencies have been considered (N = 6):

$$SDBP_{Int} = \frac{1}{N}\sum_{n=1}^{N}\frac{1}{K_n}\sum_{j=1}^{K}\left| Sound_{j-filt-n} \right| \tag{2}$$

The coefficients K_n used in the index allow normalizing it according to the different number of samples acquired during the knock angular observation window, and to the different number of frequency bands used.

In order to assess the quality of the knocking information contained in the audio signal with respect to the one that can be extracted from the cylinder pressure, the knock intensity index based on acoustic emissions has been compared with an in-cylinder pressure based knocking index assumed as a reference. In particular, the Maximum Amplitude Pressure Oscillation (MAPO) defined by equation (3) has been considered as the reference pressure-based knocking index [18].

$$MAPO = \max(\left| Pcyl_{filt} \right|) \tag{3}$$

For MAPO evaluation, the in-cylinder pressure is high pass filtered at 5 kHz. MAPO values are strictly associated to the intensity of the pressure waves produced by the auto-ignition process, and therefore to the main knock-related damage mechanisms [6].

During the tests, five full load engine operating conditions have been investigated and 2000 subsequent engine cycles have been acquired and processed for each test. In order to evaluate the performance of the sound-based knocking index the Pearsons linear correlation factor between MAPO and integral SDBP has been calculated, and the results that have been obtained are summarized in Table 3.

Table 3. Linear correlation levels obtained for experimental tests.

Engine Speed	r(MAPO,SDBP)			
	Cyl 1	Cyl 2	Cyl 3	Cyl 4
[rpm]	[%]	[%]	[%]	[%]
2000	84.43%	88.48%	85.37%	74.44%
2500	83.03%	78.69%	78.85%	77.32%
4000	90.30%	72.87%	51.57%	83.71%
4500	90.16%	91.76%	64.18%	88.40%
5000	72.58%	50.96%	43.31%	68.92%

By analyzing the results reported in Table 3, it may be noted that the correlation levels have a decreasing trend when engine speed increases. The index behavior can be related to the increase of the background noise at the highest engine speeds. For test run at 5000 rpm, the lowest correlation levels for cylinders 2 and 3 can be also partially explained by the lower knock intensity obtained for these cylinders during this specific test. The overall correlation level is sufficiently high, and almost constant for all the tests, to allow the implementation in the Engine Control Unit (ECU) of an individual cylinder spark advance controller based on acoustic emissions processing.

4. Turbocharger speed measurement

When the turbocharger runs, the compressor impeller blades create pressure waves that spread in the surrounding environment as sonic or ultrasonic sound. In this case, a frequency analysis of the acoustic emissions may isolate a main frequency contribution related to the blade or compressor round frequency. In order to demonstrate the feasibility of this approach, a specific test has been carried out on the test bench. The engine used for the test has been equipped with a turbocharger in which the compressor presents 12 blades and 6 semi-blades.

As a first step of the test, the engine and the turbocharger have been maintained under steady state operating conditions, while the compressor rotational speed was measured by means an eddy current sensor, and the acoustic emission was acquired at 200 kHz.

During the test, the average turbocharger speed was controlled at 157000 rpm, which corresponds to 15.7 kHz for the semi-blades frequency, and 31.4 kHz for the blades frequency. Figure 3(a) shows the FFT of the acoustic emission signal that has been acquired during the test.

By analyzing the FFT of the sound emissions (fig. 3(a)), it can be observed that the semi-blade frequency has higher intensity than the blade frequency, furthermore, the semi-blade frequency has the highest energy in the frequency ranges higher than 5 kHz. This signal characteristic allows to precisely identify the semi-blade frequency in the sound spectrum and, by the knowledge of the semi-blades number, it allows the indirect measurement of the turbocharger rotational speed.

Engine steady state operating conditions represent a particular driving situation such as for example driving on the highway at constant speed, while most of the time the engine is operated under transient conditions. To simulate a vehicle acceleration, an engine load profile has been performed at the test bench by controlling the waste gate opening rate profile. In this case, a FFT analysis cannot yield the right information about the compressor speed transient behavior. FFT supplies information about a periodic signal with infinite length that doesn't change its frequency and amplitude characteristics. To extract information about frequency and intensity of a signal that changes in time, a more complex analysis must be performed. Short Time Fourier Transformation (STFT) [20] has been applied instead of FFT in this case.

Figure 3 (b) reports the result obtained from STFT analysis of the acoustic emissions acquired during the turbocharger speed profile. By using appropriate signal processing techniques, it may be possible to identify the instantaneous compressor speed. Details about the specific signal processing are not reported in this paper, but they can be found in previous publications by the same authors [10].

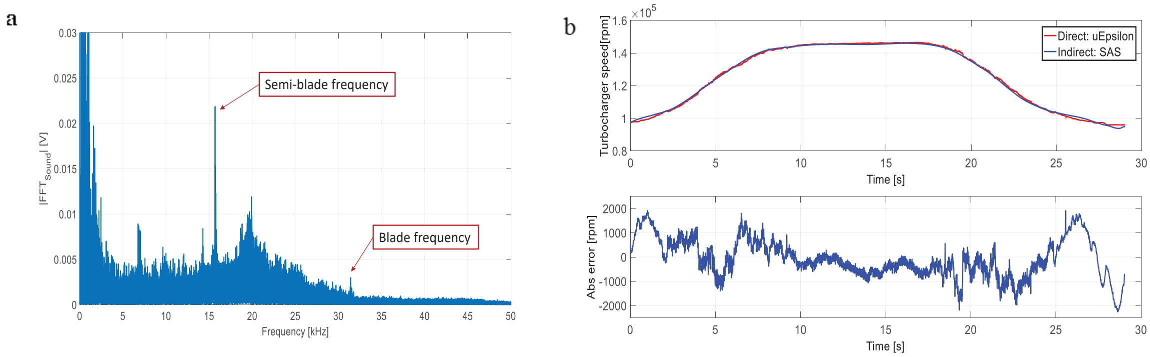

Fig. 3 Frequency analysis of sound emissions (a) steady state condition (b) transient condition

5. Misfire detection

In-cylinder pressure trace contains information related to the cylinder in which the sensor is installed, which may be called “local” information. As mentioned previously, the microphone acquires information about all the sound sources that are present in the surrounding environment. By analyzing the engine acoustic emissions in a period long as an engine cycle, it is possible to extract information related to the whole engine cycle. In this case, the sound signal contains information related to the global system (i.e., to all the engine cycles of all the cylinders). To allow a comparison between the two types of signals, the in-cylinder pressure must be converted from a local to a global signal, and it is possible achieve this goal by carrying out the sum of all the in-cylinder pressure traces. As a result, a pressure wave in which the combustion frequency is the main harmonic component is obtained. During a misfire, the pressure inside the cylinder reaches a lower level than during a normal combustion, and energy shifts from the combustion harmonic to lower components, in particular the cycle and round frequency assume a greater amplitude than during a normal cycle. Figure 4(a) shows frequency analysis of the overall pressure trace under normal and misfiring conditions, for a test run at 4500 rpm and full load. In this case, the combustion frequency is 150 Hz.

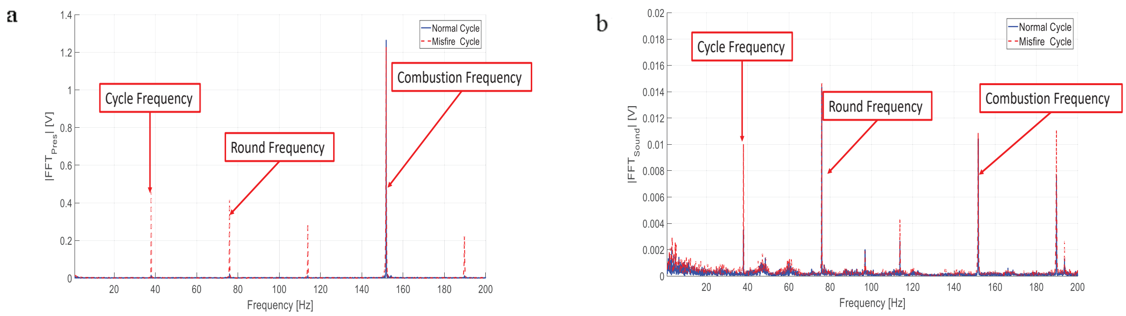

Fig.4 FFT of (a) in-cylinder pressure (b) sound emissions under normal and misfiring condition

Under normal operating conditions, the sound signal presents different frequency components, and the main harmonic is the combustion frequency. During a misfire, the sound waves emitted from the engine are modified. By comparing the acoustic emission related to a normal condition and a misfiring cycle, in the frequency domain, it may be noted that the sound signal has the same behavior of the overall pressure signal; in particular, during a misfire the signal energy shifts from the combustion frequency to the cycle frequency, as shown in fig. 4 (b).

By analyzing figure 4 (b) it may be noted that the sound spectrum is noisier than the in-cylinder pressure one. Furthermore, the round frequency under normal and misfiring condition has similar amplitude, also because some subsystems, such as, for example, the high pressure gasoline pump (for the engine taken into account) rotates and emits noise at this frequency. The cycle frequency, in the acoustic signal, changes its amplitude from normal to misfiring condition in a clear way, and therefore the occurrence of a misfire could be identified by performing in real time the amplitude analysis of this specific harmonic. Further developments of this type signal processing algorithms could also allow identifying the specific cylinder in which the misfire occurred.

6. Intake fault detection

As it is well known, air that flows through a hole from a pressurized tank emits a hiss/whistle, and the intensity of this sound is mainly due to the pressure difference between the environment inside and outside the tank and to the hole diameter. Thompson et al. [21] correlates the leak sound emissions to the interaction between the flow fluctuations inside the fluid and the tube wall.

Some preliminary tests have been performed on an engine during idle conditions, in which the intake manifold absolute pressure was 300 mbar. During the tests, three holes with different calibrated diameters have been introduced in the intake manifold, downstream the main engine throttle.

The following figure 5 shows the acoustic emissions that have been acquired during such tests. It may be noted that the sound emission becomes more intense when the hole diameter is increased.

On the basis of this experimental result, the comparison between the sound intensity acquired when the engine runs and the reference sound intensity may lead to the identification of an abnormal engine condition. More experimental tests are required in order to identify the most appropriate acoustic-based index, and to isolate a robust correlation between sound characteristics and hole diameter. Furthermore, by applying more sophisticated data analysis techniques such as beamforming [22], it could be possible to identify the space position of the leak in the engine air path, thus providing more useful and detailed information to the engine controller.

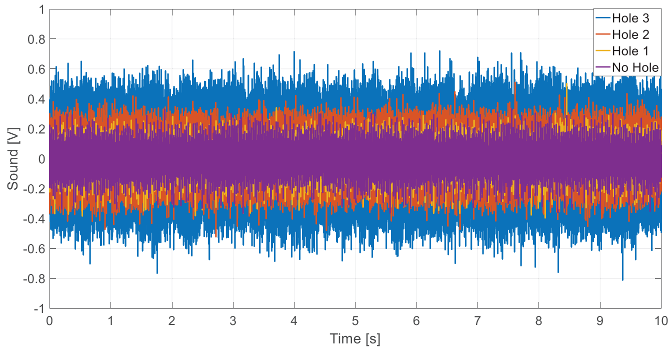

Fig. 5. Sound emission from different diameter leaks in the intake plenum.

7. Conclusion

The article shows how it is possible to extract useful information for internal combustion engine monitoring and control, through appropriate acoustic signal processing techniques. All the results that have been shown in the paper have been obtained using the very same microphone, placed in the very same position, close to the engine. The different tasks are undergoing different development stages, and some are still being further developed and optimized.

Knock identification and indirect turbo speed measurement are the most advanced algorithms, the experimental results allow to assume that these techniques could be used on-board, and tests are being performed on the vehicle to further improve their robustness.

In the field of misfire detection via audio signal processing, the first experimental results proved the possibility to reach this goal. More efforts are required to develop a robust technique, able to identify when the misfire occurred and the specific cylinder. The air path fault identification experimental tests have shown interesting results that allow the further development of this activity.

The application of these types of algorithms has allowed the development of a microphone-based sensor that could be used as a multifunction sensor able to overcome cost and reliability problems of some sensors already present on the market, and to add new functionalities.

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