

Acoustic Emission Processing for Turbocharged GDI Engine Control Applications

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ABSTRACT

In the field of passenger car engines, recent research advances have proven the effectiveness of downsized, turbocharged and direct injection concepts, applied to gasoline combustion systems, to reduce the overall fuel consumption while respecting particularly stringent exhaust emissions limits. Knock and turbocharger control are two of the most critical factors that influence the achievement of maximum efficiency and satisfactory drivability, for this new generation of engines. The sound emitted from an engine encloses many information related to its operating condition. In particular, the turbocharger whistle and the knock clink are unmistakable sounds. This paper presents the development of real-time control functions, based on direct measurement of the engine acoustic emission, captured by an innovative and low cost acoustic sensor, implemented on a platform suitable for on-board application. The real-time signal processing algorithms can be integrated in the actual ECU software, in order to improve the engine controller performance. Experimental tests have been carried out in a test-cell environment, using a downsized and turbocharged GDI engine. In order to evaluate the acoustic signal processing algorithms performance, and to prove the effectiveness of the proposed methodology, knocking was externally induced by acting on the spark advance, while turbocharger operation was controlled over wide and fast speed transients.

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INTRODUCTION

The introduction in gasoline engines of concepts such as downsizing, turbocharging and direct injection, has recently led to a significant reduction of fuel consumption and greenhouse gas emissions. During on-board operation, the turbocharger speed may be estimated by implementing a static compressor model within the Engine Control Unit (ECU); unfortunately, the compressor steady state characteristic provides inaccurate values during transient operation, and it does not consider the possibly large part-to-part variations that characterize turbochargers production. A safety margin has therefore to be guaranteed by the boost control management, with the aim of preserving the turbocharger from over speeding. Such limitation imposed on the turbocharger controller implies a suboptimal performance in terms of maximum achievable boost pressure, and of turbo-lag reduction during transient operation.

A potential solution to improve the boost control management involves the direct measurement of the rotational speed, thus enabling a more accurate closed-loop control of the turbocharger speed. Unfortunately, the use of a specific sensor for the turbocharger speed measurement is not always compatible with the cost constraints typical of mass production passenger cars. Alternative techniques, based on indirect measurements and low cost sensors, have recently

been developed and illustrated in literature [1, 2]. Another factor limiting the potential performance increase of new engine generations is the knock occurrence, which prevents from controlling the Spark Advance (SA) angle at a value corresponding to maximum combustion efficiency.

Engine sound emissions contain relevant information about its operating conditions, as demonstrated by several studies [3, 4, 5]. In particular, the characteristic whistle emitted from the turbocharger and the clink audible when knocking combustions occur, can be captured and analyzed in order to extract useful information for the engine management [2, 5].

The paper presents the development of a novel methodology to derive a knock index based on engine acoustic emissions, and to use it as the main input of a knock control strategy, based on a unique threshold level for the discrimination of non-knocking and knocking combustions. The audio-based knock controller has been implemented in a real-time algorithm, whose task is to adjust the SA, cycle by cycle and cylinder by cylinder, in order to maximize the combustion efficiency, while preserving the engine from potential damage caused by knock. The paper also shows how the very same microphone can be used to capture the sound emission of the turbocharger, to perform

an indirect measurement of its rotational speed. This dual functionality of knock detection and turbo speed measurement, achievable by using only one microphone, is demonstrated in the paper, along with the experimental validation of both methods and the final real-time implementation of the proposed algorithms.

EXPERIMENTAL SETUP

The engine used for this study is a 4 cylinder 1.4L turbocharged direct injection engine, for passenger car application. Its technical data are summarized in [Table 1](#).

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

Displacement	1390 cm ³
Stroke	75.6 mm
Bore	76.5 mm
Compression ratio	10:1
Number of Valves	4 per cylinder
Max Torque	220 Nm @ 1500-4000rpm
Max Power	103 kW @ 6000 rpm
Injection System	Direct Injection (up to 150 bar)

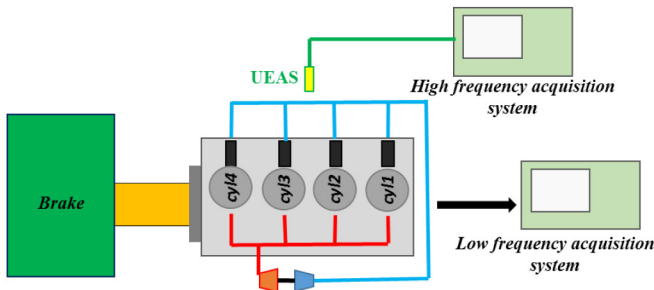


Figure 1. Sensors layout and engine test-cell installation

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 Ultrasonic Engine Acquisition System (UEAS), has been used. In-cylinder pressure and acoustic emission signals have been acquired simultaneously at 200 kHz. Knock has been externally induced by applying controlled spark advance increments, whereas turbocharger speed profiles have been performed by controlling the

waste gate opening rate. Finally, a turboSPEED DZ135 sensor (by MICRO-EPSILON), facing the compressor of the turbocharger, has been used to directly measure its rotational speed.

One of the most important aspects that must be taken into consideration when performing an acoustic analysis is the microphone position. In fact, the acoustic waves emitted by a source may be partially or totally shielded by the presence of a barrier along their path, when diffusing through the surrounding environment. Thirteen different locations around the engine have been tested during the experimental phase, in order to determine the ones that enable knocking clink and turbocharger whistle to be sensed at the same time.

COMBUSTION CHAMBER VIBRATION MODES

The combustion chamber can be considered as a bidimensional membrane that vibrates if excited by pressure waves. The vibration modes of the membrane are strictly correlated to the geometry of the combustion chamber and to the thermal state of the trapped gas [6, 7, 8]. The Draper's frequencies can be calculated by [Equation \(1\)](#).

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

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 first four vibration modes have been calculated using [Equation \(1\)](#). They are listed in [Table 2](#).

Table 2. Combustion chamber resonant modes

r,c	P	fr
[-]	[-]	[kHz]
1,0	1.84	7.67
2,0	3.05	12.72
3,0	4.20	17.52
4,0	5.32	22.19

Preliminary experimental tests were performed by inducing knocking levels of different intensity (by acting on the SA), to verify whether the in-cylinder pressure signal was actually excited at the estimated resonant frequencies shown in [Table 2](#), and whether such “signature” was observable also on the engine acoustic emission. [Figure 2](#) shows the Power Spectral Density (PSD) calculated for the in-cylinder pressure signal under non-knocking, light-knocking and heavy-knocking conditions (at a given engine speed), confirming the

sensitivity of in-cylinder pressure to knock intensity, and the resonant frequencies values calculated by Equation (1). The data shown in Figure 3 are related to the same tests of Figure 2, but in this case the PSD has been extracted from the acoustic emission signal, demonstrating that its frequency content is affected by knock in a similar way, and therefore proving that in principle the acoustic emission can be used to measure knocking intensity.

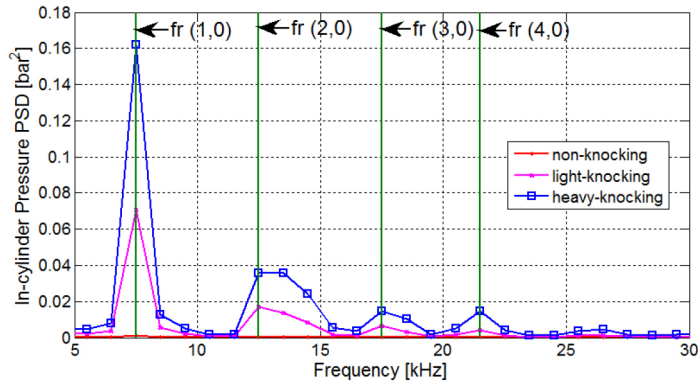


Figure 2. In-cylinder pressure signal energy distribution

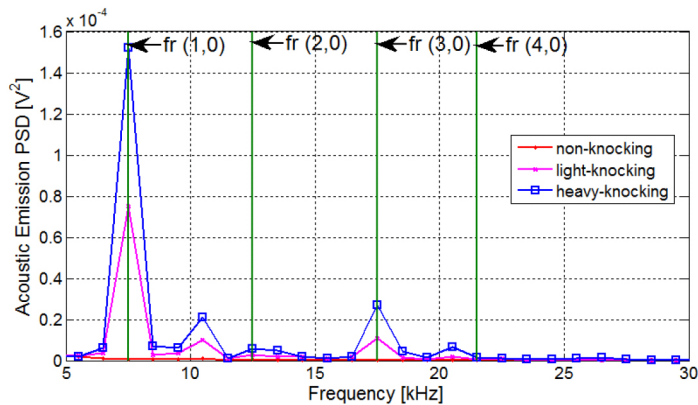


Figure 3. Acoustic emission signal energy distribution

Comparing the figures above, it may be noted that in both signals the same frequencies are excited during knocking combustions. Further, the intensity of the energy in the acoustic emission spectrum increases in the same way as for the in-cylinder pressure signal. On the other hand, observing Figure 3, it is visible that the engine sound wave spectrum contains significant frequency components that are not correlated to knock intensity. This consideration suggests that the knock detection should be performed through an analysis of frequency bands close to combustion chamber natural modes, in order to avoid the influence of other acoustic sources.

Many types of knock indexes have been developed in the last decades. A detailed review of the main approaches has been presented by Millo et al. [6], and more recently by Worret et al. [9].

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 first step of the study has been the definition of different knock intensity indexes based on acoustic emissions, and the comparison with an in-cylinder pressure based knocking index

assumed as a reference. In particular, the Maximum Amplitude Pressure Oscillation (MAPO) defined by Equation (2) has been considered as the reference pressure-based knocking index ([9]).

$$MAPO = \max(|P_{cyl_filt}|) \quad (2)$$

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 [10]. For sound based knock intensity, two different indexes have been considered [5, 11], defined by Equations (3) and (4):

$$Int = \frac{1}{\theta_2 - \theta_1} \int_{\theta_1}^{\theta_2} |Sound_{filt}| d\theta \quad (3)$$

$$SDBP = \max(|Sound_{filt1}|) + \max(|Sound_{filt2}|) + \max(|Sound_{filt3}|) \quad (4)$$

For *Int* calculation, the acoustic emission signal (*Sound*) has been band-pass filtered between 7 and 8 kHz. This frequency band corresponds to the first vibration mode, which resulted as the most sensitive in both pressure and sound signals. The frequency bands corresponding to the first three vibration modes, which resulted more evident in the acoustic spectrum, have instead been chosen for the definition of SDBP. *Int* represents the knocking index typically implemented within production ECUs for accelerometer-based knock-detection, and it is therefore particularly interesting to verify, in this study, the correlation level that may be achieved with in-cylinder pressure based knocking indexes using this type of algorithm.

The positions and widths of the angular windows used for knock evaluation for both in-cylinder pressure and sound emission are the same. Another aspect that should be taken into account, in sound analysis, is the transport time between sound emission and the moment that the sound wave reaches the microphone. By compensating this time delay, it is possible to maximize the signal to noise ratio and to assign the knocking event to the right cycle and cylinder. In the real time algorithm, the time delay has been initially estimated by measuring the air temperature and the distance between the microphone and each cylinder. The sound speed has been evaluated using Equation (5):

$$C_s = \sqrt{KRT} \quad (5)$$

Where:

K: ratio of specific heats,

R: gas constant,

T: air absolute temperature.