

Injection Pattern Design for Real Time Control of Diesel Engine Acoustic Emission

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ABSTRACT

Upcoming more stringent emission regulations throughout the world pose a real challenge, especially in regard to Diesel systems for passenger cars, where the need of additional after-treatment has a big impact in terms of additional system costs and available packaging space. Therefore, the need for strategies that allow managing combustion towards lower emissions, that require a precise control of the combustion outputs, is definitely increasing. Acoustic emission of internal combustion engines contains a large amount of information related to engine behavior and working conditions. Mechanical noise and combustion noise are usually the main contributions to the noise produced by an engine. In particular, recent research from the same authors of this paper demonstrated that combustion noise can be used as an indicator of the combustion that is taking place inside the combustion chamber and therefore as a reference for the control strategy. Previous works showed the correlations existing between in cylinder combustion and the acoustic emission radiated by the engine, and presented a possible approach to use this signal in the engine management system for control purposes. In this work, additional experiments were carried out, in order to further investigate how to design the optimal injection pattern. The application was tested by running several experimental tests, in steady state conditions, on a Diesel engine mounted in a test cell. Tests have been run in order to identify the correlation existing between the different injection/combustion patterns that can be operated on the engine and the corresponding acoustic emission, to be used in the closed-loop combustion control based on engine noise feedback.

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INTRODUCTION

Modern injection systems for Diesel engines allow designing injection patterns with a variable number of injections per cycle. In particular, the control system of the engine under investigation can perform up to 8 injections within the engine cycle, respectively named Pilot, Pre, Main, After and Multi-Post [1]. In this work, only Pilot, Pre and Main will be taken into account, since After and Post are mainly used to fulfill after-treatment needs.

The main goal of Pilot and Pre injections is noise reduction: heat released during the combustion of the amount of fuel injected in Pilot and Pre increases pressure and temperature in the combustion chamber and consequently reduces the ignition delay of the amount

of fuel injected during Main injection. Subsequently, heat released during the combustion portion associated to Main injection is predominantly mixing-controlled and it is characterized by a lower heat release peak compared to a single injection premixed combustion [2,3]. Many works in literature, some of them by the same authors of this paper, highlight the correlation between noise radiated by the engine and the magnitude of the premixed combustion portion, i.e. the magnitude of cylinder pressure rise rate [4,5]. The interruption of the injection rate, obtained splitting the total amount of fuel injected into three injections, results in a small premixed combustion portion and, consequently, in a lower radiated noise [6,7].

Additional parameters available for injection pattern design are rail pressure, Energizing Time (ET) and start (SOI) of each injection. In particular, SOI_{main} is a reference value for the whole pattern, while the angular location of Pilot and Pre is defined indirectly by setting the Dwell Time (DT) between injections. Several definitions of Dwell can be found in literature; in this study, Dwell refers to the time between the end of one energizing command and the beginning of the following. Each mentioned injection parameter has a strong influence on the way combustion takes place in the combustion chamber and, consequently, on engine-out emissions, noise and fuel consumption. Injection parameters maps are usually the output of a calibration activity aimed at obtaining the best compromise between engine efficiency and pollutant emissions, while keeping low the noise level due to the combustion process. At the same time, the chosen engine calibration is performed in such a way to run the engine in stable and reliable operating points. Many works in literature demonstrate that a further emissions or noise reduction potential is associated with the use of non-conventional injection patterns, usually characterized by low stability and reliability over time, that can be kept stable only using a closed-loop combustion control based on combustion feedbacks, such as center of combustion and torque.

As discussed in literature [8], DT reduction can provide a significant noise reduction potential for a Pilot-Main injection strategy. However, the operating condition characterized by very low noise is usually correspondent to small Dwell Times, at which very small dwell time variations correspond to high variations in the amount of fuel injected, mainly due to the rail pressure fluctuations caused by each injector opening [9]. Consequently, such operating modes are usually discarded during the calibration activity, because of the low injection stability and reliability over time.

This work analyzes the effects of Dwell Time variations on pollutant emissions and combustion noise for a 4 cylinder light duty Diesel engine run at relatively low load: 2 injections (Pilot, Main) and 3 injections (Pilot, Pre, Main) strategies have been investigated. During each test, noise due to combustion has been measured through a proper processing of both in-cylinder pressure and acoustic emission, coming from an acoustic sensor facing the engine block. The injection commands have been measured with a current clamp to provide real angular location of fuel injections. The results of the analysis show that real-time acoustic emission analysis can be used to optimize engine operation in terms of noise radiated and efficiency. In particular, the real-time calculation of a noise index can be used to feedback a closed-loop strategy for online injection pattern optimization.

EXPERIMENTAL SETUP

The analysis has been performed using a 1.3L Common-Rail Diesel engine mounted in a test cell. Table 1 summarizes the technical characteristics of the engine under investigation. As mentioned above, the Common-Rail injection system, equipped with solenoid injectors, is capable of performing up to 8 injections per cycle. However, the operating conditions analyzed in this work are characterized by three injections: Pilot, Pre, Main.

Table 1. Engine technical characteristics.

Displaced volume	1248 cc
Maximum Torque	200 Nm @ 1500 rpm
Maximum Power	70 kW @ 3800 rpm
Injection System	Common Rail, Multi-Jet
Compression ratio	16.8:1
Number of Valves	4 per cylinder
Architecture	L4
Firing Order	1-3-4-2

All the signals coming from standard and additional sensors applied to the engine can be acquired and real-time monitored. Standard sensors, already installed on the engine and present on-board vehicles for control purposes, have been monitored and sampled using INCA software and ETAS hardware. With regard to the additional sensors, the engine is equipped with one piezoelectric pressure sensor per cylinder (AVL GH14P). In-cylinder pressure signals are acquired and analyzed using an indicating system (OBI by Alma Automotive) that allows real-time calculation of indicated torque (T_{ind}) and center of combustion (MFB50). To measure the acoustic emission, one sensor has been installed facing the engine block, positioned at approximately 0.2 m on the opposite side with respect to the exhaust. Such sensor is a microphone-based sensing device developed by Magneti Marelli, characterized by a specific acoustic signal filtering [10,11].

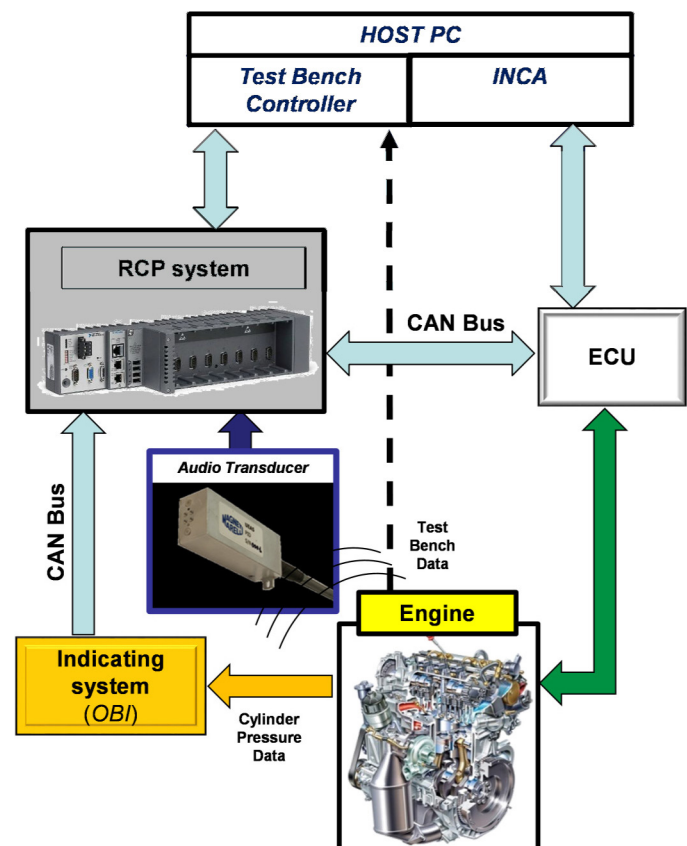


Figure 1. Scheme of the developed experimental setup.

All the acquired signals are provided as inputs to a specifically designed Rapid Control Prototyping system (RCP) for closed loop combustion control. Such system, based on a National Instruments cRio 9082, receives from OBI (indicating system) the calculated combustion indexes via CAN bus, samples at 100 Hz analog signals coming from standard sensors applied to the engine and acquires at high frequency (100 kHz) the signal coming from the microphone-based transducer using a 9215 data acquisition board. Finally, the RCP system is capable of communicating with the ECU via CAN bus to read or overwrite the values of the injection parameters of interest (Dwell Time, Energizing Time and Start of Injection). [Figure 1](#) reports a complete scheme of the developed experimental setup.

The presented setup has been used to implement a closed loop combustion controller that automatically varies the injection pattern to keep torque and center of combustion equal to their target values. Several tests have been carried out running the engine at 2000 rpm and BMEP = 3 bar, while varying the dwell time between injections.

Closed Loop Injection Controller

As discussed above, this paper investigates the effect of dwell time variations on the combustion process, the goal being to obtain a benefit in terms of combustion noise or combustion efficiency. However, Dwell Time variations, especially for low values, can have a significant impact on the total amount of fuel injected, mainly because of the rail pressure fluctuations caused by each injector opening. In particular, each injection influences the following one, and the intensity of the influence depends on the Dwell [8].

To keep the total amount of injected fuel approximately constant while varying Dwell Time, a closed loop controller that automatically varies ETmain and SOImain has been developed. In particular, the aim of the controller is to real-time correct the nominal injection pattern in such a way that torque and center of combustion are kept constant at their target values. The controller reads via ECU CAN bus the values of SOI and ET calculated by the engine control system for all the injections (Pilot, Pre and Main) of each combustion. Furthermore, the controller reads via CAN bus torque and center of combustion calculated by the indicating system. Then, ETmain and SOImain calculated by the controller depend on the difference between target and actual values of the indicated quantities. If the error between target and actual indicated quantities remains below a calibrated threshold, the RCP system overwrites (via ECU CAN bus) final SOImain and ETmain with the same values calculated by the standard engine control. Otherwise, if the error increases, the RCP system overwrites SOImain and ETmain with new calibrations calculated using 2 PID controllers. [Figure 2](#) shows a scheme of the closed loop injection controller.

The main idea behind this approach is that when the center of combustion is kept stable in correspondence of the optimal value (9 deg, i.e. the one obtained with the standard engine calibration) torque delivered by the engine is mainly dependent on the amount of fuel injected. Consequently, a controller that keeps simultaneously constant both torque and MFB50 automatically allows compensating most of the injected fuel deviations due to rail pressure oscillations.

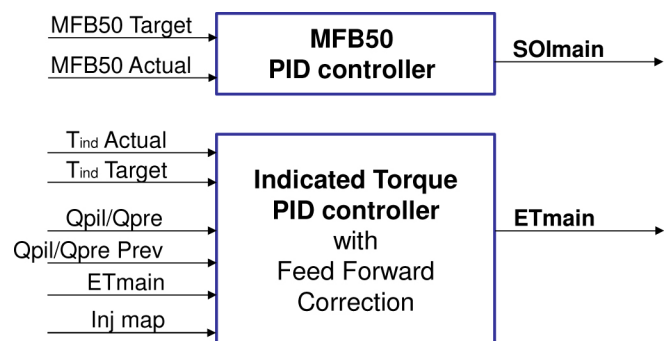


Figure 2. Scheme of the real-time injection controller implemented in the RCP system.

Noise Calculation

To investigate the potential of DT variation in terms of noise reduction, it is necessary to implement the calculation of a proper noise index. In this work, noise has been calculated both from the acquired in-cylinder pressure trace and from the signal coming from the microphone-based transducer facing the engine block.

With regard to the noise index calculated from in-cylinder pressure, the routine provided in [12] has been chosen. Such routine, almost identical to the ones used by commercial devices to compute combustion noise, calculates the Fourier Transform of in-cylinder pressure trace, filters the resulting spectrum to represent structural attenuation by the engine and the frequency response of the human ear (represented using the A-weighting filter), and integrates the resulting spectrum. Finally, the integrated filtered spectrum is normalized by the threshold of human hearing (20 μ Pa) to provide combustion noise in dB(A). As above mentioned, this routine is very similar to the one implemented in commercial devices for combustion noise calculation. Therefore, the noise index calculated from the cylinder pressure trace has been kept as a reference value.

With regard to the processing of the acoustic emission signal, the algorithm for the real-time calculation of the noise index, implemented in the RCP system, is similar to the processing applied to in-cylinder pressure trace. N-elements buffers of the signals coming from the acoustic sensor facing the engine block are processed to calculate the frequency spectrum (through the FFT algorithm). If the acquired time-based buffer $m(t)$ is an N-elements vector, the FFT returns the N/2-elements discrete spectrum (in the frequency domain) [5]. Then, the A-weighting filter, that mimics the frequency attenuation of the human hearing system, is applied to the evaluated discrete spectrum. In this work, a soft computing formulation reported in [13] was chosen. Starting from the filtered spectrum of the acoustic emission it is possible to calculate an approximation of the overall noise level perceived during each test. Named $M_A(j\omega)$ the A-weighted spectrum, [Eq.\(1\)](#) can be used to calculate the mean energy level of the signal.

$$\bar{E} = \frac{1}{N \cdot T} \cdot \sum_{k=1}^N (M_{Ak})^2$$