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Optimization of a GDI engine operation in the absence of knocking through numerical 1D and 3D modeling

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ABSTRACT

Various solutions are being proposed and adopted by manufactures and researchers to improve the energetic and environmental performance of internal combustion engines within the transportation sector. For automotive spark ignition engines, gasoline direct injection is one of the presently preferred technologies, in conjunction with turbocharging and downsizing. One of the limiting phenomena of this kind of engines, however, still remains the occurrence of knocking, namely the self-ignition of the so-called *end-gas* zones of the mixture, not yet reached by the flame front. This phenomenon causes strong in-cylinder pressure oscillations, high stress levels and even damage to engine components.

Present work focuses on a numerical and experimental study of a turbocharged GDI engine and is aimed at assessing CFD-O (computational fluid dynamics optimization) procedures to be used in the phase of design as a decision making tool for the development of control strategies for a smooth and efficient operation. A preliminary experimental analysis is performed in order to characterize the considered engine and to investigate the phenomenon of knocking that occurs under some circumstances as the spark advance is increased. The collected data are employed to elaborate a predictive criterion for the appearance of this kind of abnormal combustion, as well as to validate both a 1D and a 3D model for the simulation of the engine working cycle. Various numerical optimization procedures are then realized to increase the engine power output and simultaneously avoid conditions leading to undesired self-ignitions. These are either based on the use of a non-evolutionary algorithm or employ a genetic algorithm in the case multiple contrasting objectives are set. The response surface methodology is also explored as a way to reduce the computational effort.

1. Introduction

The current development of internal combustion engines is mainly related to the need of providing concrete answers to the increasingly stringent anti-pollution regulations and the demand for engines with great energy efficiency. These problems are important especially in the automotive field where the huge number of circulating vehicles in urban areas causes serious risks to the human health. The concern about the environmental impact of combustion processes makes indispensable the search for any strategy optimizing energy conversion.

A way to significantly improve the fuel efficiency in automotive propulsion systems, without shifting away from conventional technologies, is well recognized in the use of direct injection. Among spark ignition (SI) engines, gasoline direct injection (GDI) is preferred to port fuel injection (PFI), as coupled with downsizing and turbo-charging. The interest for gasoline direct injection derives from some simple considerations: the control of the air-to-fuel ratio can be more flexibly adapted to the specific load and speed and allows reducing the engine pumping losses at part load operation [1].

The most important issue in the development of GDI engines still remains the control of the mixture formation process, which may be realized through three different techniques, namely the *wall-guided*, the *spray-guided* and the *air-guided* mode [2, 3]. In the *wall-guided* combustion mode, the fuel vapour is directed towards the spark plug by the cylinder walls or properly shaped piston surfaces. This generates increased fuel deposits and emissions of unburned hydrocarbons and particulate matter. As an alternative, the *air-guided* combustion mode prevents the fuel from coming into contact with the walls through proper air movements, but offers a poor control of the actual air-to-fuel ratio distribution within the combustion chamber. Finally, the *spray-guided* (or *jet-guided*) combustion concept

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ensures achieving ignitable mixtures at the spark location at the time of ignition through properly positioning the spark plug in relation to the spray plume.

In any of the afore mentioned situations, looking for the optimum set of engine parameters that allows both maximizing the useful work and limiting the pollutants at the exhaust for each possible engine operating condition is a very important issue [4,5]. The objective of highest power output often determines control strategies that are at the limit of a smooth engine operation. Increasing the spark advance to get high engine work is in fact constrained by the possible occurrence of the knocking phenomenon, namely by situations in which a part of the mixture, before being invested by the flame front, reaches conditions that promote its spontaneous ignition. The self-ignition of a fuel-air mixture is the result of a series of pre-flame or low temperature reactions which lead to the start of the combustion process without the intervention of an external source, but through the formation of not stable products of partial oxidation (peroxides, aldehydes, hydroperoxides, etc.) and the release of thermal energy. When the energy of the exothermal chemical reactions exceeds the amount of heat transferred from the reagent system to the external environment, self-ignition takes place. As a result, the temperature of the mixture increases, rapidly accelerating the subsequent oxidation reactions. The speed of the pre-flame reactions, of chain type between highly reactive compounds, can be reduced through the introduction in the fuels of small quantities of additives, which hinder the formation of radicals acting as chain propagators [6–8].

Present work, that represents an elongated version of the paper presented at the ECT 2014 Conference [9], is aimed at describing numerical approaches able to point out the engine optimal operating condition for the highest engine power output and the avoidance of knocking. A turbocharged Alfa Romeo 1750 cc GDI engine, experimentally characterized at the test bench, is considered. Various alternatives are presented, which either resort to the coupling between a 3D computational fluid dynamics (CFD) model of the processes occurring in the combustion chamber and a 1D CFD model of the entire engine, or exclude from the analysis the 1D model (simplified calculation). The 1D model is developed within the GT Power environment [10], while the 3D simulation is done in AVL FIRE^{TM} [11], after proper validation of the adopted sub-models. The choice of these specific frameworks and their commercial nature are not binding, since the developed procedures have a general character and are suitable of being based also on different kind of codes, including proprietary ones.

The 3D calculations are limited to the closed valve period. When the 1D and the 3D models are coupled, the initial conditions for the 3D calculations are derived case by case from the results of the 1D code. When just the 3D model is used, the initial conditions remain unvaried. These situations are obviously comparable only in the case the intake pressure does not change. The results obtained from the two different methodologies are indeed compared in order to understand if it is worth resorting to the 1D–3D model coupling.

The computational effort of the 3D and the 1D engine model is indeed obviously different: a 3D closed valve period calculation lasts about 6 h with the employed mesh over a MPI 16 CPU 3.2 GHz workstation, while only about 5 min are needed for the 1D model. The mesh of the 3D model has a size ranging between 198807 cells at intake valve closing (IVC) and 162612 cells at the top dead center (TDC), due to so-called *rezone* procedure that allows avoiding excessive cell distortion in both the compression and the expansion strokes.

Great attention is dedicated to the knocking phenomenon, since the 3D code does not implement a chemical kinetic model for its prediction, which would increase the computational time to limits unreasonable for an optimization process. A simple criterion is therefore established in order to identify the possible occurrence of knocking. The criterion is derived from the available experimental data and is based on the evaluation of the pressure gradient with reference to a threshold value above which the *end-gas* is supposed to self-ignite [6].

The design of experiment (DOE) space of the relevant variables is properly defined case by case. Both non-evolutionary and evolutionary algorithms are used to find the solution of the optimization problems. In order to reduce the computational effort, it is shown that reduced sub-sets of data can be used to build proper response surfaces (using either the Gaussian process or the neural network methodology), which may mimic the engine behavior and allow individuating the best engine operation within low computational time [12].

The paper scope is indeed the comparison and the evaluation of the feasibility of various optimization procedures for the definition of GDI engines control strategies. Formulating and solving an optimization problem over a quite large DOE space is indeed shown not strictly needed, but, due to the low number of involved input variables and the smooth engine behavior, a map can be preliminary traced for the objective function starting from a limited number of samples. The optimal solution is here directly found. In more complex situations, an exhaustive evaluation procedure could be used as concentrated in the most promising region around the global optimum, after the response surface has been built.

Table 1
Engine details.

Engine	4 stroke spark ignition 4 in line cylinders 4 valves per cylinder Exhaust and intake variable valve timing
Displacement	1742.22 cm^3
Stroke	83 mm
Bore	80.5 mm
Combustion chamber	52.77 cm^3
Turbocharger typer	Variable geometry turbocharger
Max boost pressure	2.5 bar
Compression ratio	9.5
Max power	147.1 kW at 5.000 rpm
Max torque	320.4 Nm @ 1.400 rpm

2. Experimental characterization of the analysed GDI engine

2.1. Experimental apparatus and settings

A spark ignition GDI, inline 4-cylinder, 4-stroke, displacement of 1750 cm^3, turbocharged, high performance engine, manufactured by Alfa Romeo, is the object of the present study, although the followed approach may be transferred to other analogous propulsion systems. Mixture formation is realized in a *wall guided* mode with a 6-hole high pressure injector located between the intake valves and oriented at 70° with respect to the cylinder axis. The engine is equipped with a variation valve timing (VVT) system in order to optimize the intake and exhaust valves lift under each specific regime of operation. The engine is not equipped with after-treatment devices. All the engine details are reported in Table 1.

The experimental apparatus includes the following modules: an electrical dynamometer, the fuel injection line, the data acquisition and control units, the emission measurement system. The electrical dynamometer allows operating the engine under both motoring and firing conditions, hence detecting the in-cylinder pressure data and exploring the engine behavior under stationary and simple dynamic conditions.