

Cycle-by-Cycle Analysis, Knock Modeling and Spark-Advance Setting of a “Downsized” Spark-Ignition Turbocharged Engine

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ABSTRACT

Recently, a tendency is consolidating to produce low displacement turbocharged spark-ignition engines. This design philosophy, known as “engine downsizing”, allows to reduce mechanical and pumping losses at low load as a consequence of the higher operating Brake Mean Effective Pressure (*BMEP*). The presence of the turbocharger allows to restore the maximum power output of the larger displacement engine. Additional advantages are a higher low-speed torque and hence a better drivability and fun-to-drive. Of course, at high loads, the spark-advance must be carefully controlled to avoid the knock occurrence and this determines a substantial penalization of the fuel consumption. The knowledge of the knock-limited spark timing is hence a key point in order to reduce the fuel consumption drop at high loads.

In a previous study [1], a combined procedure for the quasi-dimensional modeling of both combustion and knock phenomena was developed and applied to a 1D thermodynamic engine model in order to find the knock-limited spark-advance at wide-open-throttle (*WOT*) conditions, for different engine speeds. In the present paper, indeed, the previous analysis is extended to

include the cycle-by-cycle variations effects. Cyclic dispersion is characterized through the introduction of a random variation on a number of parameters controlling the rate of heat release (air/fuel ratio, initial flame kernel duration and radius, EGR rate, turbulence intensity). The intensity of the random variation is specified in order to realize an Indicated Mean Effective Pressure (*IMEP*) coefficient of variation similar to the experimentally observed one.

A kinetic scheme is then solved within the unburned gas zone, characterized by different thermodynamic conditions occurring cycle-by-cycle. This allows, for a given spark timing, to estimate a statistical distribution of a properly defined knock indicator.

To the aim of validating the developed methodology, a DFT analysis of consecutive experimental pressure cycles is carried out in different operating conditions. High frequency pressure oscillations, typical of knocking occurrence, can be recognized and the statistical distribution of knocking intensity is in this way identified. Numerical and experimental results are finally compared in terms of coefficient of variation, and a good agreement is found.

INTRODUCTION

Cycle-to-cycle variations are commonly observed during the combustion process of a Spark Ignition (*SI*) engine. They mainly cause fluctuations in the rate of heat release, turning in fluctuations in the power output, fuel consumption and exhaust emissions. Their unpredictable and stochastic character pose several problems to the development of optimal engine control systems [2,3] and limits the vehicle driveability.

It is widely accepted that the early flame development deeply influences the subsequent combustion phase [4]. As known, flame kernel formation depends on local mixture composition and thermo-fluidynamical conditions at the spark plug. Injection timing and duration, actuated by the electronic control unit, is continuously adjusted by the closed-loop control system, depending on a number of signals, affected by time delays and noise disturbances. Moreover, within the cylinder, the mixing of air, fuel and exhaust gas residuals (*EGR*) is not complete, resulting in a not fully homogeneous mixture at the spark time. The random nature of the spatial and temporal fluctuations of the turbulent flow field inside the cylinder also determines cycle-by-cycle variations of the fluid-dynamic conditions near the spark electrodes. Although the complex interaction of the above phenomena is not yet fully understood, it is widely recognized that cyclic variability especially increases in the cold starting, idling, low load, and lean mixture operation [5], where the burning velocity is slow and flame development is difficult. Cyclic variability also limits the internal *EGR* levels realized at low load in VVT-equipped engines [6] to the aim of reducing the pumping losses.

Due to the above considerations, experimental and theoretical studies on cyclic variability have been mainly focused on lean mixture operation and low load conditions [7]. More recently, indeed, due to the tendency in producing low displacement ("downsized") turbocharged spark-ignition engines, the cyclic variability may play a fundamental role at high load, too. In a turbocharged *SI* engine, the spark-advance must be in fact substantially limited at high load to avoid the knock occurrence, determining a considerable penalization of the fuel consumption. However, since the spark timing is usually set for the "average" cycle, faster-than-average cycles are most likely to knock. The optimal "knock-limited" spark advance must therefore be chosen taking into account cycle-to-cycle variations.

In the present paper, basing on a previous study [1], a quasi-dimensional combustion model [8-11] is extended to characterize the cyclic dispersion of a turbocharged *SI* engine. Combustion modeling utilizes a deeply validated approach, based on a fractal schematization of the flame front surface. Cyclic dispersion is computed by introducing proper random variations on a number of parameters that affect the heat release rate (*A/F* ratio, flame kernel formation and extension, turbulence and *EGR* levels, etc.).

The combustion model, included within a 1D simulation code, is coupled to a chemical kinetic solver (CHEMKIN), for the estimation of knocking onset. The latter is carried out for each individual engine cycle through the solution of a kinetic scheme inside the "end-gas" unburned zone. This allows to estimate a statistical distribution of a proper knocking index, able to identify the presence of knocking cycles, even in the absence of knocking on the average cycle. In this way, an optimal choice of the "knock-limited" spark advance can be carried out on a completely theoretical basis.

To the aim of validating the developed methodology, a DFT analysis of consecutive experimental pressure cycles is carried out in different operating conditions. The "knock-detection" technique utilizes a methodology originally proposed by Torregrosa et al. [12,13]. The procedure quantifies the noise contribution coming from "resonance phenomena" in compression-ignition engines, occurring at autoignition time. High frequency content of the pressure cycles is recognized as an index of the knocking onset and a statistical distribution of the above indicator is in this way estimated. The coefficient of variation of the experimental and numerical knock indicators are finally compared and discussed.

ENGINE MODEL

A quasi-dimensional turbulent combustion model has been developed since many years at DIME [7-9], applying to the "wrinkled-flamelet" combustion regime. It is based on a two-zone approach and includes a fractal schematization of the flame front surface. An extensive description of the fractal model is already reported in previously cited publications. The main feature of the model is the possibility to relate the burning rate to the turbulence flow characteristics inside the combustion chamber. In particular, the fractal dimension of the flame and its wrinkling scales are defined as a function of the mean turbulence intensity inside the combustion chamber. To this end, a modified zero-dimensional turbulence model (*k-K* model [14]) is coupled to the fractal combustion model. Detailed 3D analyses carried out in [1] are utilized to accurately "tune" the 0D turbulence model. Both the combustion and the turbulence submodels are implemented in the 1D simulation code using the "user model" features of the GT-POWER® commercial product [15]. Tuning constants in both turbulence and combustion model are left unchanged in each operating condition, and assume the same values reported in [1]. They were identified in [1] with reference to a turbocharged *SI* engine very different from the one under investigation here.

Pressure cycles computed by the previously described model are compared in figure 1 to the experimental data at different engine speeds, *WOT* conditions. Experimental data are ensemble averaged over 94 consecutive cycles. In order to better appreciate the quality of the predictions, both the combustion period and the whole engine cycle are reported in a p - ϑ and $\log(p)$ - $\log(V)$ plane, respectively.

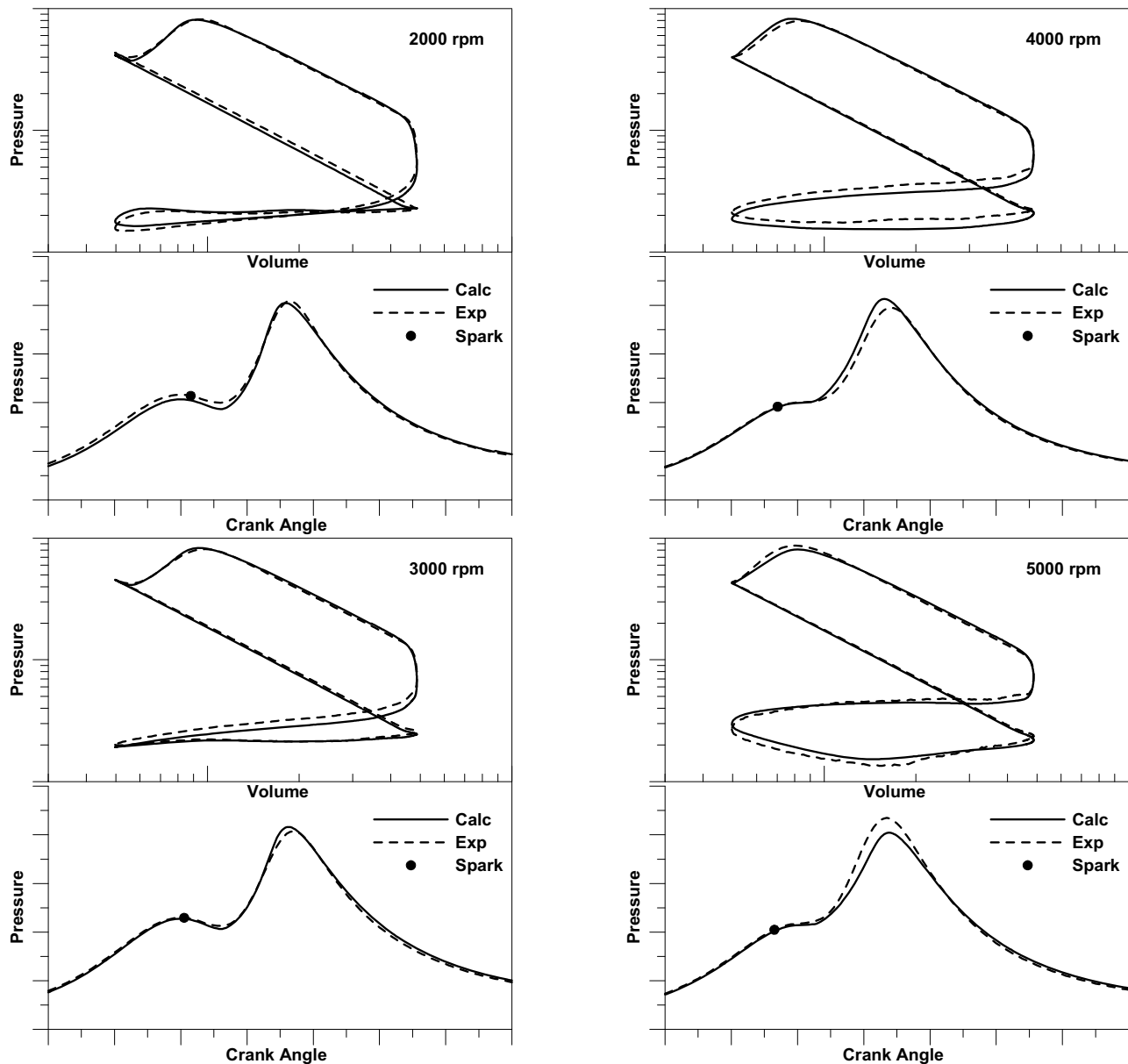


Fig. 1 - Comparisons on the average pressure cycle at different engine speeds

At each engine speed the spark timing, outlined in fig. 1, is set as the maximum allowable advance for a knock-free operation on the average cycle. The above value is experimentally derived basing on an accelerometer signal, located on the engine block. A very retarded combustion process is established especially at low speed, producing the presence of two pressure peaks. The angular delay between the spark and the time of first pressure rise is well reproduced by the model. Moreover, the satisfactory agreement along the compression stroke and during the pumping loop suggests that a good matching with the turbocharger and an adequate simulation of the unsteady flow in the intake and exhaust systems is obtained. The latter consideration is also proved by the comparison on the air flow rate, displayed in fig. 2.

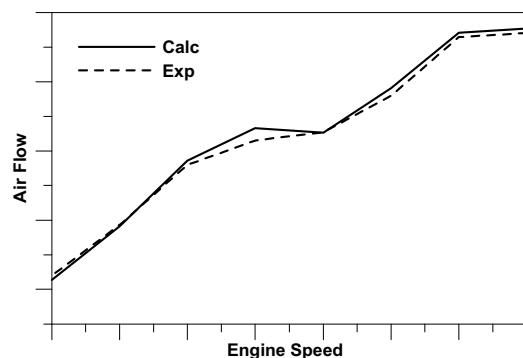


Fig. 2 – Computed and measured air flow rate