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Using large-eddy simulation and multivariate analysis to understand the sources of combustion cyclic variability in a spark-ignition engine

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ABSTRACT

The origins of cyclic combustion variability (CCV) in spark-ignition engines are investigated using large-eddy simulation (LES) of a stable (low CCV) and two unstable (high CCV) operating points of a specifically dedicated experimental test-rig set up around a four valve pentroof single cylindre spark-ignition engine fueled with a premixture of gaseous propane and air. The unstable points are obtained from the reference by reducing significantly the equivalence ratio and by an important dilution by nitrogen respectively. A LES methodology is proposed and shown to be able to reproduce the experimental findings concerning phase-averaged mean and statistical variations around it of a number of key engine combustion parameters. The CCV and factors causing it are first illustrated by comparing typical slow and fast burning cycles in combination with simple correlation plots of major engine parameters, this allows qualitatively showing how local and global sources concur to generate CCV. In a second step, single parameter and multivariate regressions build from the LES results allow quantifying the relative importance of different local and global CCV sources. Finally, the comparison of the obtained findings as to the relative importance of major parameters on CCV is compared with qualitative summary from an extensive experimental survey by Ozdor et al. The presented LES results overall confirm major findings from the survey, but also indicate that detailed causes of CCV depend on the type of engine and its operation.

1. Introduction

The operation of spark-ignition engines (SIE) is characterised by a non-repeatability of instantaneous combustion rate between different cycles at nominally identical engine operating conditions, commonly referred to as cycle-to-cycle variation [1,2] or cyclic combustion variability (CCV). CCV inevitably appears over the whole engine operation range, due in particular to the unsteady, cyclic and turbulent nature of flow and combustion in SIE. It is common practice to consider that a CCV amplitude (measured in terms of standard deviation of indicated mean effective pressure (IMEP), normalised by its mean value) of less than around 5% is acceptable [3]. As long as the CCV amplitude is sufficiently small, engine simulation softwares can predict with sufficient accuracy combustion using statistical approaches as RANS (Reynolds-Averaged Navier–Stokes) that neglect cyclic variations and aim at reproducing a phase averaged, statistically most probable, cycle. For higher CCV amplitudes however, individual cycles will behave very differently from this statistically most probable cycle. As a result, predictions of fuel consumption or emissions over a number of cycles may differ quite substantially from the one based on the mean engine cycle. These differences increase with the CCV amplitude and may reach extreme levels in the case of misfires or extreme knocking cycles [4,5].

In a context of increasingly stringent constraints on fuel consumption, CO_2 production, and pollutant emissions from road transport, it becomes crucial to be able to predict and control individual engine cycles, and thus to address the occurrence and effects of CCV. Engine technologies as downsising [6,7], direct injection (DI) [8] or controlled auto-ignition (CAI) [9,10] are examples of technologies presently explored in order to reduce the CO_2 emissions from future SIE. Yet the occurrence under certain operating conditions of excessive CCV when implementing these technologies is one of the factors limiting their practical performance or range of operation. Being able to predict CCV in early design phases based on an improved knowledge of their sources and effects could effectively contribute exploiting the full potential of these promising SI technologies under real operation.

The understanding of how the complex combination of different sources leads to the occurrence of CCV for a specific engine design

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or mode of operation is still limited. CCV is indeed the result of a complex combination of different flow phenomena. These phenomena can be classified into two main categories, depending on the related spatial and temporal scales:

- Global phenomena [11,12], which are related to global operating characteristics: trapped mass, intake mass flow rate, tumble ratio, overall equivalence ratio, mean cylinder pressure, mean intake charge temperature, exhaust gas recirculation (EGR) rate, etc. Their spatial scales are of the order of some characteristic dimensions of the engine, and their time scales of the order of the crank angle and up to the duration of an engine cycle;
- Local phenomena [13–15], which are related to local flow variables: temperature, pressure, mixture composition, turbulence, flow velocity, strain rate, etc. Their spatial scales range from some micrometers up to some millimeters, their time scales from some microseconds up to the crank angle.

Both scales can exhibit cycle-to-cycle variations and do strongly interact, making the understanding of CCV complex. This is especially true in the combustion chamber, where the non-linear response of combustion is a key contributor to CCV.

Experimental studies [11,12] certainly allow identifying CCV for a given engine concept, and they can help testing control strategies to limit its occurrence and impact. Aleiferis [16] conducted research on a pent-roof single-cylinder port fuel injection engine fueled with a stratified mixture of iso-octane/air. He concluded that the flame area was highly correlated to the crank angle at which 5% fuel mass fraction was burnt, while the flame volume was highly correlated to spark energy. In a recent paper [3] the impact of the ignition system on the combustion in a direct-injection engine was studied, showing that larger spark gaps, longer spark life durations and multi-spark ignitions were beneficial to the extension of the dilution limit and to the combustion stability. Such experiments only come into play once a prototype has actually been built, in design phases where modifications to the basic concept are difficult to achieve because of cost and time constraints. Furthermore, the achievable understanding is limited by the impossibility to have access to all necessary thermodynamic and flow quantities on an instantaneous, cycle resolved basis. Nevertheless this is required to gain a basic understanding of the sources of CCV. The understanding gained from such studies is thus only partial and rarely valid beyond the specific studied case.

Large-eddy simulation (LES) is a 3D-CFD technique that has the potential to address the numerous coupled phenomena influencing engine combustion, and potentially gives access to any quantity needed to understand and characterise CCV. Its ability to deal with turbulent flows [17–20] and reactive flows [21–23] in SI engines has been demonstrated. But only a few LES studies were dedicated to the prediction of CCV [24–26] using either the Thickened Flame (TFLES) [27], or the Extended Coherent Flame (ECFM-LES) [28–30] combustion models and the AVBP code[1] [31,32]. Vermorel et al. [26] have applied the LES models developed by Richard et al. [28] to explore the origins of CCV in an SIE fueled with gaseous propane using AVBP. They have demonstrated that computing 10 consecutive complete four-stroke engine cycles allowed reproducing experimental findings on CCV. They also illustrated how analysing this LES could be used to identify sources of CCV. In the studied case they were found to be stochastic in nature and related to the turbulence of the intake flow, and its coupling to spark-ignition and flame propagation. Lacour et al. [33] have acquired the SGEmac experimental database dedicated to a detailed study of CCV in an optical access single cylinder SIE fueled with a homogeneous mixture of propane and air. Low CCV operating points were acquired in order to fully characterise the engine and allow model validation. Two operating points were then explored in order to characterise high CCV values resulting either from an important dilution by nitrogen of the fresh gas mixture (EGR emulation), or by reducing the fuel/air equivalence ratio. Available data comprise crank angle resolved measurements of pressures and temperatures at different locations in the engine set-up, as well as visualisations of velocities and combustion progress using optical diagnostics. This database has served for validating the prediction of CCV using LES. In [34], LES of the flow under motored (without combustion) conditions were performed with AVBP and were shown to yield an accurate reproduction of the flow field inside the combustion chamber and of the acoustics in the intake and exhaust ducts. In [24] and [25] the same numerical set-up around AVBP was used for LES of fired operations. The simulation of 25 consecutive full cycles of the stable and 50 cycles of an unstable operating point in [24] using the TFLES combustion model [27] demonstrated the ability of the employed LES approach to quantitatively predict the CCV levels observed experimentally. Qualitative analysis of the LES was performed to understand the causes for incomplete combustion which occurred in some cycles of the high-CCV case, but no quantitative analysis was proposed that could have allowed correlating CCV with global or local phenomena.

The present work aims (i) at complementing these studies of CCV with an alternative LES methodology based on AVBP, (ii) at both reproducing experimentally observed CCV in the SGEmac engine, and (iii) at proposing a systematic way to explore and quantify its sources. While the above mentioned studies were based on simulating the whole engine set-up with LES, the computational domain including the whole intake and exhaust lines between the intake and exhaust plena, the present work is based on an alternative LES methodology [35], exploiting system simulation of the intake and exhaust ducts to impose unsteady boundary conditions for the LES of the combustion chamber and its immediate neighbourhood. Furthermore, premixed combustion is addressed using ECFM-LES [26,28], a LES formulation of the widely used Coherent Flame Model.

The objective of the present work is threefold:

- apply the LES methodology developed and validated for motored operation in [35] to fired operation based on the ECFM-LES combustion model, and demonstrate its ability to reproduce experimentally observed CCV levels;
- acquire a basic understanding of the origins of CCV and of their impact, as a result of both global and local phenomena;
- propose a systematic method for analysing LES of CCV in order to identify major parameters affecting it, and providing a quantification of their relative importance.

Section 2 starts by describing the experimental set-up and main characteristics of the SGEmac engine. Section 3 then details the numerical set-up of the LES of the SGEmac engine, and gives key elements of the proposed LES methodology. A first validation of the latter is provided in Section 4, which compares LES predictions of phase-averaged cylinder pressure and its variability for the reference low-CCV (or stable) operating point with experimental findings. Section 5 then presents the reproduction of experimental CCV findings for two high-CCV (or unstable) operating points of the SGEmac database achieved with the developed LES methodology. A first investigation of the CCV origins is proposed based on the visualisation of the flame propagation and by examining the degree of correlation between IMEP and the different combustion and flow characteristics. Finally, a multivariate regression model built from LES results, allows to quantify the relative importance of different local and global CCV sources and classify the degree of importance of several phenomena acting on CCV.

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[1] http://pantar.cerfacs.fr/4-26334-The-AVBP-code.php.