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Using Large Eddy Simulation to quantify cycle-to-cycle variability in spark-ignition engines

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Abstract — *Large Eddy Simulations (LES) of a spark-ignition piston engine have been performed to study cycle-to-cycle variations (CCV) on operating points presenting low (called stable) and high (unstable) levels of variability. The engine is fueled with perfectly premixed propane/air and the unstable point is obtained by diluting the mixture by a high amount of N_2, which decreases the flame speed. The results are compared with experiments, on a dedicated bench which has been specifically built to study CCV. Results show that LES is able to distinguish a stable operating point from an unstable one. As expected, CCV are enhanced by the variations in flow motion around the spark plug at spark timing.*

INTRODUCTION

Cycle-to-cycle variations (CCV) in internal combustion engines are detrimental in terms of combustion efficiency, and are thus essential to understand and control to further optimize overall engine efficiency. If the possible sources of CCV are well known [1], their identification with experimental diagnostics only is a tough task due to their strong and complex interactions. The combination of both experiments and numerical simulations, which benefit from the ongoing increase of computational power, opens new perspectives. In particular, the Large Eddy Simulation (LES) approach appears as a very suitable tool, able to deliver detailed unsteady information. Recent computations of multiple consecutive cycles in realistic piston engine configurations have demonstrated the potential of LES to capture CCV [2, 3, 4]. Nevertheless, the lack of detailed experimental data often allowed a partial validation of the LES technique only.
The present study aims to demonstrate and validate the LES ability to capture and quantify CCV thanks to a dedicated experimental database acquired on a single cylinder Spark-Ignition engine.

1 CONFIGURATION AND NUMERICAL SETUP

The engine rig reprensented on Fig. 1 is instrumented with multiple pressure and temperature transducers.

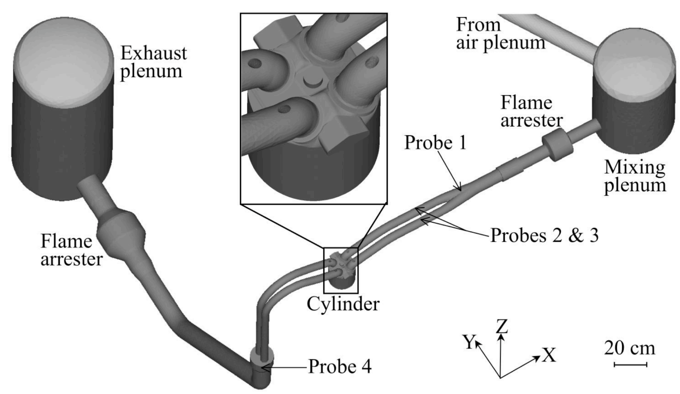

Figure 1 : Experimental set-up and computational domain.

It also includes optical diagnostics to characterize mean and fluctuating characteristics of the flow dynamic (Particle Image Velocimetry) and flame propagation (OH Laser Induced Fluorescence) [5]. LES is applied almost on the whole experimental setup to provide a simple and accurate description of the boundary conditions: the computational domain extends from the intake plenum to the exhaust plenum including the full intake and exhaust lines [6]. Two fired operating points are investigated:

- the first operating point is a stable case (i.e.

with low CCV levels : covariance of maximum peak pressure is around 5%) fueled with a stoichiometric propane-air mixture;
- the second one exhibits high CCV levels (covariance of maximum peak pressure around 12%). The instability is here achieved by alteration of the flame speed via N_2 dilution of the propane-air mixture.

Figure 2 shows the two operating points simulated in a Peters diagram to highlight their differences. The unstable point, which presents lower flame speeds due to dilution, is more sensitive to turbulence in the combustion chamber.

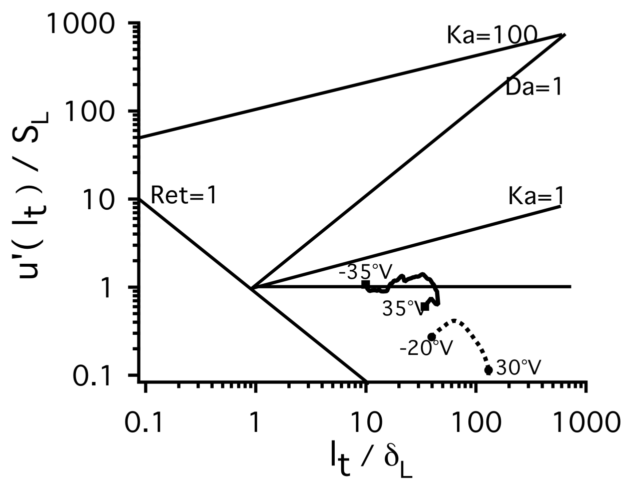

Figure 2 : Peters diagram [7], stable point (- -) and unstable point (-).

LES computations are performed with the AVBP code [8,9] which solves the multi-species Navier-Stokes equations on unstructured grids. The current LES covers 25 consecutive cycles for the stable point and 15 consecutive cycles for the unstable point. For each cycle, 41 grids are used to describe the moving geometry. Typical meshes are composed of several billions of tetrahedral elements. The moving grid management is handled by an Arbitrary Lagrangian Eulerian (ALE) method combined with a Conditioned Temporal Interpolation (CTI) technique. The target pressures are time-varying signals extracted from experimental data. Combustion is modeled using:

- A reduced two-step chemical scheme for propane/air flames validated over a wide range of operating pressure and temperature [10].
- An ignition model [11] which adds a volumetric source term in the equation of energy.
- The dynamically thickened flame model to reproduce the local conditions of flame/turbulence interactions [12].

2 STABLE OPERATING POINT

Table 1 presents the results of the LES simulations on the CCV of maximum pressure. The level of CCV reached by the LES is within the range of the experimental variation. Figures 3 and 4 present the evolution of the cylinder pressure for the 100 experimental cycles and the 25 LES cycles respectively : a very good agreement is achieved. Since the statistical sample is of the same range between LES and experiment and the in cylinder pressure evolution is comparable, a cycle-by-cycle analysis of the LES simulation is possible to understand the discrepancies observed between a cycle and another in the combustion duration.

	$\sigma(P_{max})$					
Cycles	1-25 %	26-50 %	51-75 %	76-100 %	**1-100 %**	LES 1-25 %
STABREF	3.7	4.6	5.5	4.7	**4.7**	4.6

Table 1 : CCV of maximum pressure for the stable point.

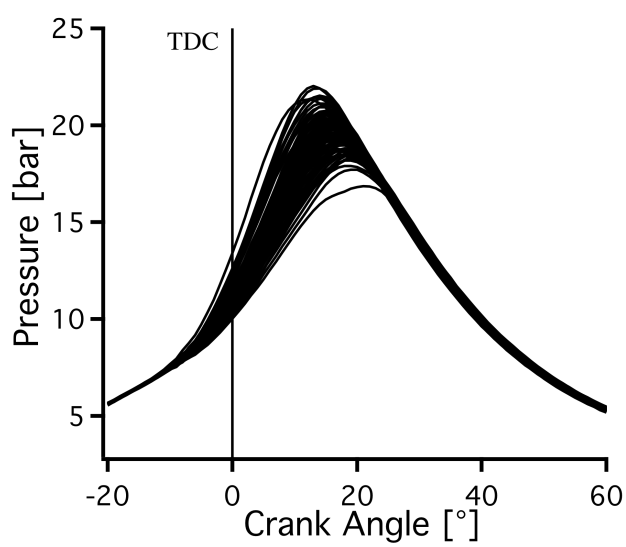

Figure 3 : Experiment cylinder pressure for 100 cycles (stable case).

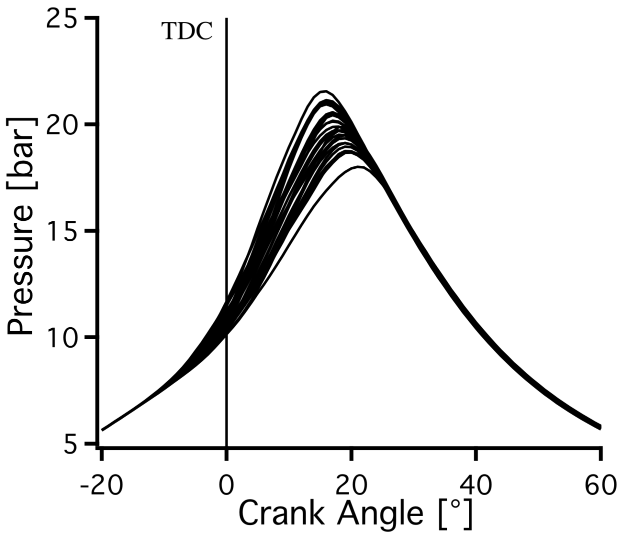

Figure 4 : LES cylinder pressure for the 25 cycles (stable case).

3 UNSTABLE OPERATING POINT

Table 2 presents the CCV on the maximum pressure for the unstable point. Although the number of simulated cycles is too low (more cycles are underway to achieve a higher statistical sample), LES predicts variations which are within the experimental range. LES seems to be able to differenciate an unstable and a stable operating point.

	$\sigma(P_{max})$					
Cycles	1-25 %	26-50 %	51-75 %	76-100 %	**1-100 %**	LES 1-15 %
INSTDIL	15.1	10.0	11.0	11.7	**12.4**	13.3

Table 2 : CCV of maximum pressure for the unstable point.

Figures 5 and 6 illustrate the good prediction of LES regarding the in-cylinder pressure.

4 CONCLUSIONS

The present work presents LES simulations of consecutive cycles of a spark ignition-engine compared with experiments. It shows that LES is able to capture the CCV levels of two different operating points : a stable one (low CCV) where 25 cycles are simulated and an unstable one (high CCV achieved by N_2 dilution) where 15 cycles are performed.

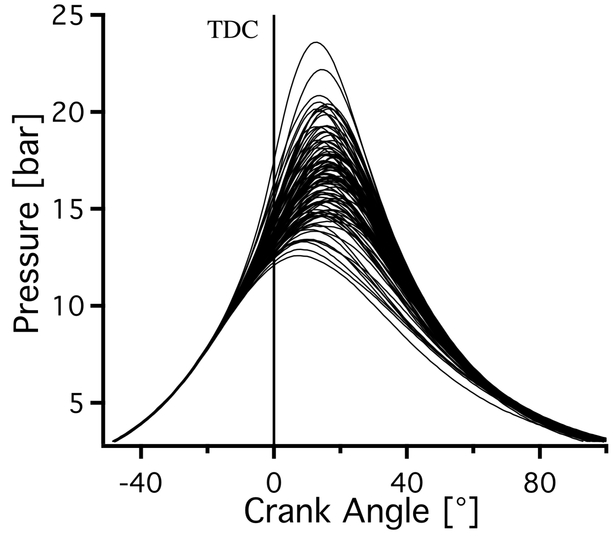

Figure 5 : Experimental cylinder pressure for the 100 cycles (unstable case).

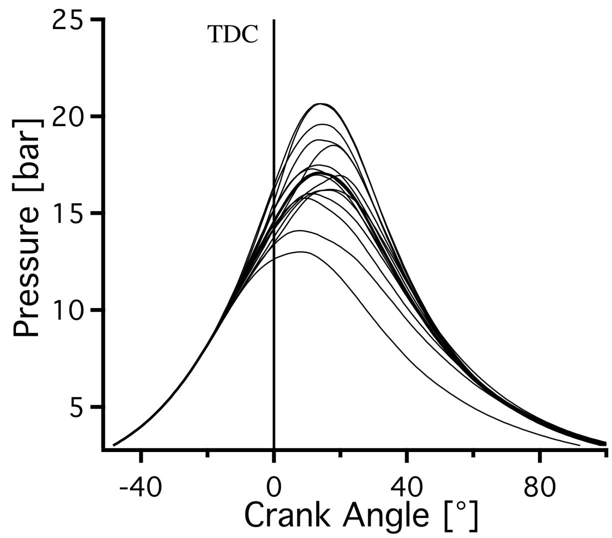

Figure 6 : LES cylinder pressure for the 15 cycles (unstable case).

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REFERENCES

[1] N. Ozdor, M. Dugler, and E. Sher. Cyclic variability in spark ignition engines, a literature survey. SAE Paper, (940987), 1994.

[2] O. Vermorel, S. Richard, O. Colin, C. Angelberger, A. Benkenida, and D. Veynante. Towards the understanding of cyclic variability in a spark ignited engine using multi-cycle LES. Combust. Flame, 156:1525–1541, 2009.

[3] D. Goryntsev, A. Sadiki, M. Klein, and J. Janicka. Large eddy simulation based analysis of the effects of cycle-to-cycle variations on air-fuel mixing in realistic DISI IC-engines. In Proc. Combust. Inst., 32:2759–2766, 2009.

[4] C. Hasse, V. Sohm, and B. Durst. Numerical investigation of cyclic variations in gasoline engines using a hybrid URANS/LES modeling approach. Comput. Fluids, 39(1):25–48, 2010.

[5] C. Lacour, C. Pera, B. Enaux, O. Vermorel, C. Angelberger, and T. Poinsot. Exploring cyclic variability in a spark-ignition engine using experimental techniques, system simulation and large-eddy simulation. In Proc. of the 4th European Combustion Meeting, 2009.

[6] B. Enaux, V. Granet, O. Vermorel, L. Thobois, V. Dugué, and T. Poinsot. Large eddy simulation of a motored single-cylinder piston engine: numerical strategies and validation. Flow, Turb. and Combustion, In press, doi: 10.1007/s10494-010-9299-7, 2010.

[7] N. Peters. Turbulence Combustion. Cambridge University Press, 2001.

[8] N. Gourdain and L.Y.M. Gicquel and M. Montagnac and O. Vermorel and M. Gazaix and G. Staffelbach and M. Garcia and J.-F. Boussuge and T. Poinsot. High performance parallel computing of flows in complex geometries – part I : methods. Comput. Science and Discovery, 2, 2009

[9] N. Gourdain and L.Y.M. Gicquel and M. Montagnac and O. Vermorel and M. Gazaix and G. Staffelbach and M. Garcia and J.-F. Boussuge and T. Poinsot. High performance parallel computing of flows in complex geometries – part 2 : applications. Comput. Science and Discovery, 2, 2009

[10] B. Enaux, V. Granet, O. Vermorel, C. Lacour, C. Pera, C. Angelberger and T. Poinsot. LES study of cycle-to-cycle variations in a spark ignition engine. Proc. of the comb. Inst., doi:10.1016/j.proci.2010.07.038, 2010.

[11] G. Lacaze, E. Richardson and T. Poinsot. Combust. Flame 156 : 1166—1180, 2009.

[12] O. Colin, F. Ducros, D. Veynante and T. Poinsot. A thickened flame model for large eddy simulations of turbulent premixed combustion. Phys. Fluids, 12 (7) : 1843-1863, 2000.