Massively parallel LES of azimuthal thermo-acoustic instabilities in annular gas turbines

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Abstract. Most of the energy produced worldwide comes from the combustion of fossil fuels. In the context of global climate changes and dramatically decreasing resources, there is a critical need for optimizing the process of burning, especially in the field of gas turbines. Unfortunately, new designs for efficient combustion are prone to destructive thermo-acoustic instabilities. Large Eddy Simulation (LES) is a promising tool to predict turbulent reacting flows in complex industrial configurations and explore the mechanisms triggering the coupling between acoustics and combustion. In the particular field of annular combustion chambers, these instabilities usually take the form of azimuthal modes. To predict these modes, one must compute the full combustion chamber comprising all sectors, which remained out of reach until very recently and the development of massively parallel computers. A fully compressible, multi-species reactive Navier-Stokes solver is used on up to 4096 BlueGene/P CPUs for two designs of a full annular helicopter chamber. Results show evidence of self-established azimuthal modes for the two cases but with different energy containing limit-cycles. Mesh dependency is checked with grids comprising 38 and 93 million tetrahedra. The fact that the two grid predictions yield similar flow topologies and limit-cycles enforces the ability of LES to discriminate design changes.

1. Introduction
To enhance combustion for cleaner and more efficient engines implies new designs and operating ranges, usually by using lean combustion. Unfortunately, these technological choices often lead to combustion instabilities that sometimes take the form of azimuthal modes in annular gas turbines [1, 2, 3, 4]. Strong coupling of acoustics and non-linear heat release results in thermo-acoustic instabilities that can appear as both standing or rotating modes [5], though it has been shown in [1] that the rotating mode is more likely to be found when considering the limit cycle.

To predict these modes requires to understand the underlying physics governing the stability of annular gas turbines. Experimental studies require full test rigs that are complex and rare. Numerically, the study and prediction of annular chamber stability can be achieved by using one dimensional networks [1, 6] or Helmholtz solvers [7, 8]. These methods rely on the concept of the flame transfer function [9], which remains a key element and needs to be evaluated, using Large Eddy Simulation (LES) for example, or modeled [4, 9, 10]. Although LES could potentially predict combustion instabilities, until recently its use was restrained to the modeling of the flame transfer function obtained on a single sector simulation. LES of the full combustion chamber stayed out of reach until very recently through the development of massively parallel computers.
Today, full annular chambers can be computed on massively parallel machines by running LES codes on a thousand to several thousand processors, producing real engine operating conditions and their thermo-acoustic activity (limit-cycle).

A fundamental but unfortunately often neglected issue is the effect of mesh resolution on numerical results. As LES is based here on implicit filtering of the governing equations, hence by the grid size, the question of mesh dependency has been qualified as being of utmost importance by several authors [11, 12]. However, mesh dependency has been addressed mostly in academic configurations [13, 14] or for single sector configurations [15]. The computing power that is available today makes it possible to compute two grids of 38 and 93 million elements, representing a full annular helicopter chamber, and thus to compare the results in terms of mean and fluctuating fields and subgrid scale (SGS) quantities. This first comparison allows to obtain grid criteria that can then be used in an industrial context: i.e. to qualify two designs in terms of thermo-acoustic activity.

To start addressing such issues for industrial applications, two full annular versions of the considered helicopter engine only differing on the design of the swirlers are computed and analyzed with regard to their thermo-acoustic stability.

The LES code and the models used throughout this study are described in the next section. The target configurations are exposed before conducting an analysis of the effects of mesh resolution on the mean flow and on thermo-acoustic response of one of the two designs. LES results that help discriminating the two designs in terms of thermo-acoustic stability are then discussed.

2. Numerical tools and target configurations

The numerical tool used here is called AVBP [16]. Co-developed by CERFACS1 and IFP2, it solves the three-dimensional Navier-Stokes equations on unstructured and hybrid grids. Based on the LES approach [4, 11, 17], it is able to account for the influence of reacting and two-phase flow phenomena. In this investigation, the SGS stresses are modeled using the Smagorinsky approach [18] while combustion is modeled using Arhenius type reaction rates. The fuel is JP10 [15, 19], which is a surrogate for Kerosene. The interaction between the flame and turbulence is considered with the Dynamic Thickened Flame (DTF) model [20, 21, 22]. The third-order numerical scheme TTGC [23] is used. Multiple validations of the LES tool have been published [24, 25, 26]. The code has been thoroughly tested in all possible architectures available today (Power, Opteron, Xeon, Sicsortex, etc...) and has exhibited excellent strong scaling performances on most super-computers (Fig. 1).

The base configuration (Fig. 2) considered throughout this study is a full annular reverse-flow helicopter gas turbine demonstrator designed by Turbomeca (Safran group). The whole chamber is computed with its casing, which helps avoiding uncertainties on the boundary conditions. Indeed, the calculated domain starts immediately after the compressor’s outlet, and extends to a choked nozzle corresponding to the throat of the high pressure distributor (Fig. 2). Fuel is supposed to be totally vaporized and only gaseous phase is computed. Air inflow feeds the combustion chamber through the swirlers, cooling films and dilution holes. Multi-perforated walls used to cool the liners are taken into account by a homogeneous boundary condition [27].

Two grids with different resolutions are compared to assess the impact of mesh resolution on LES: a light one that comprises 37.7 million tetrahedral cells and a fine one, composed of 93.1 million tetrahedral cells. Typical time steps are $5.9 \times 10^{-8}$ and $3.1 \times 10^{-8}$ seconds respectively.

Two variants of this annular helicopter gas turbine are computed. Version A and B only differ by the swirlers’ design, the combustion chamber itself remains the same and is equipped with

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1 http://www.cerfacs.fr
2 http://www.ifp.fr
Figure 1. Strong scaling for the AVBP CFD tools on a variety of super computers.

Figure 2. 3/4 view of the fully annular combustion chamber and boundary conditions shown on a single sector.

fifteen burners. Each swirler consists of two co-annular counter-rotating swirl stages. Differences between version A and B are geometrical details.

3. Results
The lighter grid has been run on 2,048 processors on a SGI Altix Ice 3 equipped with Intel Xeon 3GHz CPUs. LES of 0.1 seconds physical time required around 400,000 CPU hours. The fine grid case has been run on 4,096 processors on an IBM Blue Gene/P and 3,000,000 CPU hours were required to perform a LES of 30 ms physical time. Those two LES reveal almost identical results. The flow topology, not presented here, is the same. Figure 3 displays the mean temperature fields on a transversal cut of a single sector and infers similar combustion regimes on both meshes. Note also that the thermo-acoustic behavior obtained from both grids draws analogous conclusions. Mesh convergence is reasonable in terms of mean and fluctuating quantities with the lighter grid resolution. The lighter mesh resolution is thus chosen for computing the two variants of the chamber (Version A and B).

3 GENCi: http://www.genci.fr - CINES: http://www.cines.fr
4 Argonne National Laboratory - ALCF: http://www.anl.gov
When considering these two swirler designs, self-established azimuthal modes are observed. However, the two cases exhibit very different limit-cycles. Version A presents intense fluctuations of heat-release and flame position, whereas version B displays weaker pressure fluctuations and better flame anchoring. Figure 4 shows the pressure RMS profiles for both versions on a developed line containing all swirlers’ axis and indicates the same mode structure. However, version B demonstrates dimmer fluctuations when compared to version A, which presents strong local peaks corresponding to each swirler’s exit and result in much more perturbed flame fronts. Based on such observations, version B is recommended since qualified as more stable by LES for the considered operating point.

4. Conclusion

Combustion instabilities, which can dramatically alter correct operation of engines, are a crucial issue. Large Eddy Simulation is a very promising path to apprehend thermo-acoustic instabilities
in complex geometries. Massively parallel architectures offer the potential to compute full annular gas turbines. For the first time, a 15-sector full annular helicopter chamber has been simulated and reveals self-established azimuthal modes. Effects of grid resolution have been addressed and proved the light mesh to be adequate for the analysis. Two variants of this chamber, differing by geometrical details of the injection system, have then been gauged against each other and LES is able to discriminate the two cases in terms of azimuthal thermo-acoustic stability.

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