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

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Increasingly stringent regulations and the need to tackle rising fuel prices have placed great emphasis on the design of aeronautical gas turbines, which are unfortunately more and more prone to combustion instabilities. In the particular field of annular combustion chambers, these instabilities often take the form of azimuthal modes. To predict these modes, one must compute the full combustion chamber, which remained out of reach until very recently and the development of massively parallel computers.

In this paper, full annular Large Eddy Simulation (LES) of two helicopter combustors, which differ only on the swirlers’ design, are performed. In both computations, LES captures self-established rotating azimuthal modes. However, the two cases exhibit different thermo-acoustic responses and the resulting limit-cycles are different. With the first design, a self-excited strong instability develops, leading to pulsating flames and local flashback. In the second case, the flames are much less affected by the azimuthal acoustic mode and remain stable, allowing an acceptable operation. This study therefore highlights the potential of LES for discriminating injection system designs.

INTRODUCTION

More than eighty percent of the energy produced worldwide is created by combustion of fossil fuels that has severe effects on the environment and is greatly responsible for global climate change. Moreover the fuel resources are dramatically decreasing. Combined to the fact that nowadays there is no real substitute to combustion for many applications such as aeronautical engines, optimizing the process of combustion is the key answer to control those issues. To enhance combustion implies new designs and operating ranges for engines, usually by using lean combustion. Unfortunately, these technological choices lead to combustion instabilities that often 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].

To predict and avoid these modes requires a deeper understanding of the underlying physics governing the stability of annular gas turbines. Experimental studies require full test rigs, which are costly and rare. Numerically, the study and prediction of annular chamber stability can be achieved by using one dimensional networks [6, 7] or Helmholtz solvers [8, 9]. However these methods rely on the concept of the flame transfer function, which remains a key element and needs to be evaluated or modeled using Large Eddy Simulation (LES) for example. Although LES could potentially predict combustion instabilities, 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 thousands of processors, producing real engine operating conditions and their thermo-acoustic stability.

Following a previous study by Staffelbach et al. [10] two helicopter engines, only differing on the design of the swirlers, are presented and compared. The first section describes the LES code and the models. The target configurations are then exposed before presenting the LES results that help discriminating these two designs in terms of thermo-acoustic instabilities.

I LES AND NUMERICAL MODELS

LES is known to be able to predict reacting flows [4, 11, 12], stability of flames [13] and flame-acoustic interaction [14, 15]. In this paper, a fully compressible unstructured explicit code is used to solve the
reactive multi-species Navier-Stokes equations [16, 17, 18]. A third order finite element scheme is used for both time and space advancement [19]. Sub-grid stress tensor is modeled by a classical Smagorinsky approach [20]. Boundary conditions are implemented through the NSCBC formulation [21, 22] and wall boundaries use a logarithmic wall-law approach [15].

Chemistry is computed by means of a reduced one-step mechanism for JP-10 / air flames. This mechanism is fitted to match the full scheme’s behaviour for equivalence ratio between 0.4 and 1.5 [23]. Five species are explicitly transported and solved: \( J P_{10}, O_2, CO_2, H_2O \) and \( N_2 \). To better capture flame/turbulence interactions, Dynamic Thickened Flame (DTF) model is use [24, 25].

### II Target Configurations

Two variants of an annular helicopter gas turbine are computed in this study. Version A and B only differ on the swirlers’ design, the combustion chamber itself remains the same and is equipped with fifteen burners. Each swirler consists of two co-annular counter-rotating swirl stages. Differences between version A and B are geometrical, the separator between inner and outer swirling stages has a different shape.

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, where inlet profiles are known, and extends to a choked nozzle corresponding to the throat of the high pressure distributor (Fig. 1). Fuel is supposed to be totally vaporized and only gaseous phase is computed to simplify the LES. Air inflow is at 578 K and 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 an homogeneous boundary condition [26].

The final full annular mesh for version A is made of 9,009,065 nodes and 42,287,640 tetrahedral elements. Typical time step for this configuration is \( 7.5e^{-8} \) seconds. The version B mesh contains 6,916,125 nodes and 37,696,365 tetrahedral elements and has a typical time step of \( 5.9e^{-8} \) seconds. The initial conditions for version A and B are obtained from statistically converged single sector LES with periodic boundary conditions that are azimuthally duplicated fourteen times (Fig. 2). In the following, each of the fifteen burners is numbered starting with sector 1 placed at \( z = 0 \) and \( y > 0 \) and increasing clockwise.

### III LES of Two Helicopter Engines

Version A and B have 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 corresponding to 196 hours of execution time.

Figure 3 shows snapshots of the temperature field on a cylindrical plane containing the swirlers’ axis for version A and B. An observation of this field versus time (not presented here) shows that, in both cases, the flames oscillate azimuthally and axially with time. The oscillation is more pronounced for version A.
with visible flash-backs of the flame in the swirlers. That behavior is not observed in version B predictions. Figure 4 provides a better insight of this phenomenon by showing instantaneous pressure fluctuation and temperature fields on a developed surface that corresponds to the cylinder of Fig. 3 at a given instant but for only part of the full annular chamber. Pressure fluctuation fields clearly reveal the propagating azimuthal pressure waves for both versions. As these waves meet the flames, the latter move back and forth as well as from left to right.

Figure 5 shows the time-averaged temperature fields for version A and B. The flames present very different mean shapes. A flames have more perturbed fronts whereas B flames all exhibit V shaped fronts. B type swirlers provide clean and stable re-circulation zones in front of each burner allowing a steady anchoring region for the flames. On the contrary, A type swirlers generate unstable re-circulating zones imposing strong flow variations to the flames which result into large local heat-release fluctuations.
Time-averaged pressure fluctuation fields ($\frac{P_{\text{RMS}}}{P_{\text{mean}}}$) are presented on Fig. 6 for version A and B. The visualization is obtained in the developed surface of Fig. 5. The azimuthal development of the RMS pressure fields indicate two zones of high fluctuations separated by two relatively calm zones in both cases. Version B predictions present much less pressure fluctuations when compared to case A, demonstrating that the amplitude of the pressure wave is smaller for version B [10]. The differences in pressure variations are confirmed by Fig. 7 where $\frac{P_{\text{RMS}}}{P_{\text{mean}}}$ are plotted for both cases along a line contained in the developed surface and located in front of all burners’ exits. Figure 7 shows higher maximum magnitude of pressure fluctuations for version A and much lower minimum values for version B. Note also that fifteen local peaks appear on the pressure profile of version A’s predictions. These strong local variations coincide with the fifteen burners for which flame positioning is not stable enough and explains such levels of fluctuations. Such peaks are barely observed for version B, indicating that this injection system is much more stable and much less sensitive to acoustic forcing. Note that such a statement can be quantified through the evaluation of the integrated value of the pressure RMS profiles provided on Fig. 7. That is $121.538$ and $79.913$ for version A and B respectively: i.e. a 34% reduction of the pressure activity. Most of the reduction is for this diagnostic due to one factor: type A swirlers provide a pressure RMS field with no quiet zone and large amplitude variations. All burners of that chamber are subject to acoustic pressure fluctuations. Such a behaviour is explained by the superposition of two contra-rotating waves with

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Figure 4: Developed surface of a cylinder containing the swirler’s axis for half the burners. From top to bottom: Temperature field with temperature isocontours, pressure fluctuations with $P'=0$ isoline at a given instant. The left and right columns correspond respectively to type A and B chambers.

Figure 5: Time-averaged temperature fields on a developed surface of a cylinder containing the swirler’s axis for all burners for version A (top) and B (bottom).
one mode containing more energy than the other [10, 1, 2, 3, 4]. Type B chamber, on the other hand, has several burners subject to almost no acoustic forcing. This indicates the presence of two equal energy containing contra-rotating waves resulting into the first azimuthal eigenmode of the system.

![Figure 6](image)  
**Figure 6**: Pressure fluctuation levels on a developed surface of a cylinder containing the swirler’s axis for all burners: top, version A and bottom, version B.

One mechanism evidenced in version A simulations and potentially at the source of the strong self-sustained oscillating operating point, is the acoustic forcing of the mass-flow rate through each burner [10]. Indeed such variations will impact the mixing of fuel with air prior to its combustion inside the chamber, as well as the hydrodynamic stability of the recirculation zone positioned in front of each swirler. These flow rate fluctuations can then perturb combustion, which can feed the thermo-acoustic instability loop. This assumption is corroborated by Fig. 8, which shows pressure fluctuations and mass flow rates through the swirlers for different sectors. Mass flow rate is normalized as: $\dot{m} = \dot{m} - \dot{m}_{\text{average}}$ and pressure as: $P = P - P_{\text{average}}$, where ($\Delta P$ is the overall pressure loss of the chamber). Figure 8 reveals sinusoidal fluctuations of pressure and mass flow rate for all sectors and for both versions. Mass flow rate and pressure are linked: when the pressure is minimum, the mass flow rate through the swirlers is maximum and inversely. This general mechanism is observed for both cases and all sectors. Case B, however, evidences sectors where the amplitude of these fluctuations is strongly reduced (see for example sectors 2 and 11 on Fig. 8) with time contrarily to case A. Further analysis is required to explain such behaviours and differences between

![Figure 7](image)  
**Figure 7**: $\frac{P_{\text{RMS}}}{P_{\text{mean}}}$ on a line passing by all burners’ axis for version A and B.
the two cases.

**Figure 8**: Swirler mass flow rates and pressure fluctuations over time for sectors 1, 2, 7 and 11.

**IV Conclusion**

LES of two versions of a full annular helicopter combustion chamber were performed using massively parallel computations. Both cases reveal a self-established azimuthal acoustic modes. The resulting rotating pressure waves perturb the flames axially and azimuthally. These waves also modulate the mass flow rate through the swirlers. However, the two cases are found to present different thermo-acoustic response and one case demonstrates a much quieter operation than the other one. Thus, the potential of LES for discriminating injection systems and predict stability of combustion chambers is highlighted.
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REFERENCES


