Thermo-acoustic stability of a helicopter gas turbine combustor using Large Eddy Simulation

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ABSTRACT
Compressible Large Eddy Simulation (LES) of turbulent reacting flows potentially offers a realistic representation of the physical phenomena involved in thermoacoustic instabilities. Coupled with Helmholtz solvers, which provide a mean of identification of the acoustic eigenmodes in complex geometries, that advanced numerical tool may provide a very powerful environment to assess the stability of real engine combustion chambers. The common use of a fully unstructured LES solver and a Helmholtz eigenmode tool proves here to be very useful to diagnose two operating points of a real gas turbine chamber which are known to operate with self-sustained oscillations. If the geometrical complexity and proper computational domain are chosen, the two thermo-acoustic instabilities are very well reproduced. Predictibility of LES for such problems is thus demonstrated provided that issues pertaining to the inlet acoustic impedances can be properly answered.

Key words: Thermo-acoustic stability, Industrial GT, Large Eddy Simulation, Helmholtz solver

1. INTRODUCTION
Ongoing developments of gas turbine engines suffer from increasingly stringent objectives and regulations. Among the new targets imposed by governments, pollutant and noise emissions \cite{16} are of prime importance. To meet these new objectives, industry has identified lean partially premixed combustion as the most promising technological solution \cite{20}. That answer however comes with a major difficulty: thermo-acoustic instabilities \cite{2, 19, 27}, which infer higher risks since only identified while benchmarking the final engine.

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Thermo-acoustic oscillations naturally arise when combustion couples with the acoustic eigenmodes [19, 30] of a given configuration. Under certain circumstances, it yields a self-sustained mechanism which can amplify until destruction of the engine. The energetic balance which discriminates the amplified regimes from the damped ones is minute and difficult to assess a priori at the design stage. However, nowadays increasing computing capabilities offer new strategies for the diagnosis on thermo-acoustic instabilities. Large Eddy Simulation (LES), which solves for the spatially and temporally evolving field in complex reacting flow configurations [4, 11, 31, 36], constitutes a very promising and powerful tool. Recent computations prove LES to be quite successful in predicting the thermo-acoustic behaviour of laboratory-scale burners [12, 38, 40]. Its extension to industrial configurations remains nonetheless to be illustrated and validated in light of the numerous difficulties generated by such an exercise. This observation also applies to acoustic eigenmode identification since, contrarily to academic burners, real combustion chamber eigenmodes cannot be identified easily beforehand. Issues pertaining to boundary conditions are of course crucial for eigenmode acoustic solvers but also for LES. Likewise and for both approaches, the computational domain to be retained for proper evaluation of acoustics in the real engine is also of great importance and goes hand in hand with the notions of acoustic impedances at the engine inlets and outlets [18, 15].

As a first attempt to gauge state-of-the-art LES in the context of gas turbine thermo-acoustic instabilities, two operating points of a given industrial demonstrator are investigated by LES. These two engine regimes are known to exhibit self-sustained thermo-acoustic instabilities. Note however that experimental measurements are limited due to the difficulty to obtain advanced and detailed diagnoses for such a configuration. The fully three-dimensional, time-dependent LES relies on a multi-species reacting gaseous compressible solver. In this work, LES predictions are supplemented by Helmholtz solver ones [25, 35] to differentiate the aerodynamic fluctuations from the acoustic ones. For the last computations, the combustion effect is solely represented by the mean flow fields issued by the unsteady predictions and no coupling between combustion and acoustics is taken into account: i.e. the amplification or attenuation of the identified eigenmodes is not investigated through the use of the Helmholtz solver. This question is addressed by use of LES since, with this unsteady time-dependent approach, the most amplified acoustic mode should naturally arise and dominate the predictions. For the proposed configuration, the computational domain used for LES and acoustic eigenmode computations encompasses the combustion chamber, the swirler and the casing to limit boundary condition effects. Experimentally, the two operating points are found to oscillate with distinct preferred directions. The first point involves axial fluctuations of pressure while the second point oscillates in the azimuthal direction. To specifically address these differences, two sets of LES predictions are studied. The first set focuses on the axial fluctuations and LES is thus conducted on an axi-periodic sector of the real engine to reduce computational costs. The second set of LES considers the full annular chamber: i.e. no boundary condition in the azimuthal direction. A similar approach is adopted for the Helmholtz computations.

The paper is organized as follows. First, information concerning the geometry of the combustion chamber, the computed operating points and the observed instabilities are
detailed in section 2, followed by a succinct presentation of the Helmholtz solver. A brief description of the LES code and models used for the closure problem is given in section 3. Main flow features obtained by LES are then presented for the two regimes and as issued by an axi-periodic sector. Specific unsteady diagnoses are devised at that occasion to evidence the coherence between these computations and the acoustic eigenmode predictions before concluding on the thermo-acoustic activity in the longitudinal direction. To finish, predictions on the full annular LES and for the second operating point are detailed in terms of azimuthal thermo-acoustic stability. Finally, concluding remarks are given on the capabilities of LES to properly predict thermo-acoustic instabilities of real gas turbine engines.

2. CONFIGURATION AND EIGENMODES
In this section, a description of the combustion chamber mounted on the engine demonstrator is provided. Technological design choices that are usually not present on laboratory-scale burners are specifically highlighted. The eigenmode acoustic analysis is then presented in order to confirm the behaviours reported experimentally during testing of the real engine demonstrator.

2.1. Target configuration
The target configuration, Fig. 1, corresponds to an annular reverse-flow combustion chamber of a helicopter gas turbine. The combustor is fed with liquid fuel by fifteen double-staged counter-rotating swirlers. The computational domain either focuses on a 24 degree section or on the full combustion chamber, designed by Turbomeca (SAFRAN group). It contains the liner, a fuel injection system and the casing. As the present study aims at accurately predicting acoustic phenomena, defining acoustic behaviour of the boundary conditions is crucial. The computational domain hence encompasses all of the parts located between the compressor diffuser and the nozzle guiding vanes, where the flow is choked (acoustic waves cannot go upstream). The casing supplies the liner and the injection system with air coming from the compressor. The atomizer, located in the swirler, provides a spray of $J P - 10$, which evaporates in the flow generated by the swirler. The rich premixed mixture is burnt in the primary zone through a flame stabilized close to the liner dome by a huge central toroidal recirculation zone. Primary jets, located on the inner and outer liners, bring additional fresh air to consume remaining fuel and prevent the combustion zone from spreading further downstream. Combustion products are then cooled in the dilution zone before reaching the nozzle guiding vanes. Cooling systems are placed all over the liner to shield walls from the hot gases. Cooling films are massively located in the return bend whereas multi-perforated plates lie on the walls of the intermediate zone and the liner dome.

2.2. Acoustic eigenmodes
The operating points, which are studied here, approximately correspond to the idle regime (Point 1) and a cruising regime (Point 2). Preliminary studies are first obtained on this complex computational domain using a Helmholtz solver. It solves the linearized acoustic wave equation in the Fourier domain, which gives the complex frequency (stability analysis) and spatial structure of all acoustic eigenmodes [3]. The Helmholtz
equation is obtained by linearizing the reacting Navier-Stokes equations under the following assumptions \[3, 9\]: low Mach number, no volume forces, linear acoustics, large scale fluctuations (long wavelength), homogeneous mean pressure, constant polytropic coefficient $\gamma$. The fluctuating pressure field is then given by the wave equation\(^1\):

$$\nabla \cdot \left( c^2 \nabla p' \right) + w^2 p' = 0, \quad (1)$$

with the following boundary conditions:

$$Z(\omega) = \frac{p'}{\rho c \nabla p' \cdot \hat{n}}, \quad (2)$$

where $Z(\omega)$ is the local impedance at the domain boundaries, $p'$ is the acoustic pressure, $c$ the sound speed, $\omega$ the frequency, $\rho$ the density and $\hat{n}$ the outward pointing normal.

\(^1\)For this example, the effects of the active flame on the pressure field are neglected \[3, 28\]
The system (1)–(2) is discretized using finite element formulation [3] to be able to handle complex geometries such as gas turbine combustors. Several examples of the Helmholtz solver application have already been referenced [25] and showed the accuracy of the solver.

Figure 2 presents acoustic pressure fields (absolute value of the acoustic pressure fluctuation) of the first two acoustic modes obtained for both regimes. Note that both regime picture such modes. The only difference is in the associated frequencies which reduce to a unique value if expressed in terms of the Helmholtz number to suppress the frequency dependency on the overall speed of sound which changes with the operating point. It is to be noted here that diffuser and high-pressure distributor are not meshed for these calculations but are replaced by acoustic impedances determined using the method described in [15]. The inlet impedance is specified to be purely non-reflective by lack of knowledge on its real value at the compressor outlet. Note that the same value will be applied for the LES predictions presented below. The first acoustic mode, Fig. 2(a), corresponds to the first longitudinal mode and does not exhibit any azimuthal dependency. The acoustic activity mainly occurs in the casing and the maximal acoustic pressure is located in the lower casing cavity. The second acoustic mode, showing a noticeable azimuthal structure along with a less intense longitudinal activity, is found to be the first azimuthal mode. Note that taking into account flame/acoustics interaction (using a Flame Transfer Function [13, 42]) could modify the acoustic shape of the presented modes. Shapes are nonetheless in very good agreement with the reported experimental observations obtained on the real engine.

The results provided by the Helmholtz solver reveal the very complex nature of the acoustic modes occurring in such realistic configurations. It is also underlined that for these predictions, the casing and the swirler (as well as any other flow calibrating section) are found to be necessary for good quality predictions. Information about the mode stability remains inaccessible as presented here. For that specific diagnosis, LES can provide valuable information as it can handle coupling with other physical phenomena such as combustion or aerodynamics.

3. LES APPROACH
A brief presentation is provided here for the computational choices adopted in LES of the examined configuration. Focus is here given on the chemical model introduced to provide information on the gaseous combustion taking place in the burner. Specific modelling issues pertaining to the LES approach are not detailed here but are available in other works [28, 29]. Finally, presentations about the mesh and geometrical simplifications introduced in the computation are provided.

3.1. LES models
The massively parallelized LES code used here solves the Navier-Stokes equations for compressible multi-component fluids [24]. Convective terms are discretized using a third order accurate two-step Taylor-Galerkin scheme [8, 10], which provides high spectral resolution and both low numerical diffusion and dispersion. Diffusive terms are treated with classical Galerkin method [10]. Subgrid contributions are expressed
Figure 2: First acoustic modes ($||p'||$) found by the Helmholtz computation for the studied configuration and for both operating points. Both shapes coincide with the experimentally directions reported for the oscillations of the engine: (a) longitudinal mode with a $He$ number of 0.3 and (b) azimuthal mode with $He = 0.37$. 
following the Smagorinsky model for the subgrid stresses [39], while gradient diffusion models are used for the scalar equations with constant turbulent Schmidt and Prandtl numbers [32].

### 3.2. Combustion modelling

Another key issue when dealing with thermo-acoustic stability concerns is the proper modelling of the combustion process and its interaction with local turbulence. The chemical kinetics must be able to return the correct adiabatic flame temperature and flame speed for a large range of equivalence ratio. The combustion model has also to deal with complex combustion regimes such as partially premixed regime or diffusion flames. LES of turbulent reacting flows implies the modelling of SGS combustion terms. The model employed here is the Dynamic Thickened Flame (DTF) model [7]. Following the theory of laminar premixed flames [43], the flame speed $S_0^L$ and the flame thickness $\delta_0^L$ may be expressed as:

$$S_0^L \propto \sqrt{\lambda L A}, \text{ and } \delta_0^L \propto \frac{\lambda}{S_0^L} \sqrt{A},$$

where $\lambda$ is the thermal diffusivity and $A$ the pre-exponential constant. Increasing the thermal diffusivity by a factor $F$, the flame speed is kept unchanged if the pre-exponential factor is decreased by the same factor [6]. This operation leads to a flame thickness which is multiplied by $F$ and easily resolved on a coarser mesh. Additional information needs however to be supplied so as to properly reproduce the effect of the subgrid-scale interaction between turbulence and chemistry [2, 1, 17]. This is the intent of the so-called efficiency function, $\varepsilon$ [7]. When thickening is applied everywhere in the flow, the model is limited to fully premixed combustion. To compute partially premixed or non-premixed flames [28], a modified version of the Thickened Flame model (DTF) is used here [17, 19, 33].

With the DTF model, the SGS fluxes are modified to become:

$$\overline{J_i'} = -(1-S)\bar{p}D_i^\alpha \frac{W_{i\alpha}}{W} \frac{\partial \tilde{X}_\alpha}{\partial x_i} + \bar{p} \tilde{Y}_\alpha V_i^c,$$

for SGS species fluxes, where $D_i^\alpha$, $W_{i\alpha}$, $X_\alpha$ and $Y_\alpha$ are, respectively, the molecular diffusivity, molecular weight, molar fraction and mass fraction of species $\alpha$, and $V_i^c$ is the correction velocity introduced to ensure mass conservation, and:

$$\overline{q_i'} = -(1-S)\lambda_i \frac{\partial \tilde{T}}{\partial x_i} + \sum_{\alpha=1}^{N} \overline{J_i'^\alpha} \tilde{\rho}_\alpha^\alpha$$

for SGS heat fluxes. $S$ is a sensor detecting reaction zones and $\lambda_i$ the thermal conductivity. The local thickening factor depends on the local mesh size: typically
thickening must ensure that enough points are present within the flame zone and the thickening factor $F$ is given by:

$$F = 1 + (F_{\text{max}} - 1) S, \quad \text{and} \quad F_{\text{max}} = \frac{N_c}{\Delta x} \delta L,$$

(6)

where $N_c$ is the number of points used to resolve the flame front ($N_c = 5$ to 10). Although this approach is still being developed and further validations are needed, its ease of implementation and its success in prior applications [19, 33, 37] suggest its suitability for the problem addressed in this work.

The chemical scheme selected in this framework is a one-step model for $JP - 10$/Air combustion, derived from a detailed scheme containing 43 species and 174 steps (Turbomeca private communication).

$$JP - 10 + 14O_2 \rightarrow 10CO_2 + 8H_2O$$

(7)

This basic single-step model suffers from a lack of precision for rich regimes. As local equivalence ratios encountered in the target configuration can reach a wide range of values, from pure fuel to pure air, a fitted pre-exponential function is introduced and dependent to the local equivalence ratio to obtain the correct flame speed on the rich side. This modified scheme thus returns proper values of flame speed on the whole range of equivalence ratios, as shown on Fig. 3. Adiabatic flame temperatures remain unchanged as reactions have not been modified on the rich side. The final expression of the reaction rate writes:

$$\dot{Q} = A(\Phi) \left( \frac{\rho Y_{JP-10}}{W_{JP-10}} \right)^{n_1} \left( \frac{\rho Y_{O_2}}{W_{O_2}} \right)^{n_2} \exp\left( -\frac{T_a}{T} \right) \text{mol.m}^{-3}.\text{s}^{-1}$$

(8)

where $n_1 = 1.5$, $n_2 = 0.55$, $T_a = 3608.4K$, and $A(\Phi)$ has been defined for each operating point as the mean pressure is noticeably different for each of them.

### 3.3. Meshes and boundary conditions

Due to the overall complexity of the combustion chamber, few geometrical simplifications are introduced to obtain reasonable time steps and ease mesh generation. The exit nozzle guiding vanes are replaced by an equivalent section which keeps the flow choked. Keeping the sonic throat in the computational domain allows to both maintain the correct mean pressure and have the right acoustic impedance. Another change in the geometrical details concerns the cooling films, which in reality are composed of drilled tiny holes in rows, connecting the casing to the combustion chamber, Fig. 1. As these holes cannot be directly resolved by the mesh, they are replaced by few larger holes whose total surface remains unchanged. Cooling films thus do not need the application of a boundary condition and the only inlet boundary conditions to be imposed are the main air inlet of the casing, the fuel inlet and multi-perforated plates. Two-phase flow
aspects are not taken into account in this study and fuel is introduced in the gaseous phase. The liquid fuel spray, present in reality, impacts on the splitter inside the swirler and the resulting liquid film is convected until it reaches the end of the splitter. It is then atomized and evaporated between the two counter-rotating flows issued by the two swirling vanes. To best reproduce the distribution of fuel and mixing in the primary

Figure 3: Chemical scheme for JP – 10: comparisons between the detailed scheme and the derived fitted one-step model for (a), the laminar flame speed and (b), the adiabatic flame temperature for both operating points simulated in LES.
zone, gaseous fuel is introduced in the computation at the location of the spray impact on the splitter, Fig. 4. Finally multi-perforated plates are modelled [5, 21, 22] and do not require extensive meshing. Note that only the blowing part of these plates is taken into account by the boundary conditions. Suction sides are replaced by walls and the corresponding flow rate is substracted from the compressor air inlet condition. This air inlet uses a Navier-Stokes Characteristic Boundary Condition (NSCBC [23, 26]) to control its acoustic behaviour and is modified to fix the mass flow rate. In agreement with the previous acoustic simulations, the main air inlet boundary condition is set to be non-reflecting. Walls are considered adiabatic and are treated with a turbulent law-of-the-wall to account for boundary layer effects. Side boundaries of the computational domain are axi-periodic in the case of a single sector.

The unstructured mesh generated for the axi-periodic sector contains 2, 819, 176 tetrahedric elements and more than 42 million for the full burner (the single sector mesh is simply duplicated to obtain the complete burner). Special attention is devoted to the primary zone and the swirler to ensure flame stabilization while preserving decent resolution of specific hydrodynamic structures.

**Figure 4:** Fuel injection methodology retained for the study (Note: not to scale or with the proper aspect ratio).
Figure 5: Overview of the unstructured mesh used for LES: (a) is a longitudinal cut and (b) is a detailed view of the primary zone.
4. RESULTS

LES predictions are presented for the single sector computational domain first. With this simplification, both operating points exhibit a self-sustained oscillation throughout the domain. Detailed analyses clearly highlight a thermoacoustic instability with the expression of a longitudinal eigenmode and in agreement with the real engine. The azimuthal oscillation of the second operating point is on the other hand only accessible by performing LES of the full annular combustor as presented in subsection 4.2.

4.1. Single sector LES predictions

The two regimes are studied using LES for the single sector configuration. A primary benefit of LES is its intrinsic capability to widely inform about instantaneous flow fields, as pointed out in Fig. 6 depicting temperature field along with a reaction rate isosurface colored by axial velocity. This instantaneous result evidences the unsteady behaviour of the flow taking place inside the combustion chamber: i.e. the huge wrinkling of the flame front (despite the use of the DTF model), represented here by the reaction rate isosurface and the complex velocity field passing through it. Mean velocity and temperature fields (Figs. 7 and 8 respectively) indicate a very similar behaviour for both operating points. The strong swirling flow induced by the injection system generates a wide central toroidal recirculating zone (typical of these devices), which confines combustion to the primary zone and enables the flame front stabilization close

Figure 6: Instantaneous view of the single sector LES computation. Plane colored by temperature and reaction rate isosurface colored by axial velocity.
Figure 7: Mean axial velocity fields obtained for (a) Point 1 and (b) Point 2.
Figure 8: Mean temperature fields obtained for (a) Point 1 and (b) Point 2.
to the swirler outlet. Primary jets contribute to the confinement of the main flow to the primary region, while cooling devices protect liner walls by creating a thermal boundary layer. Note that the multi-perforated plates tend to create a quite homogeneous cold gas layer over the walls whereas cooling films generate flat jets which rapidly mix with surrounding hot products of combustion. Detailed analyses of the main flow structures underline the dominance of the aerodynamics induced by the swirler. As shown on Fig. 9, depicting isosurfaces of Q criterion [14] inside the injection system, a Precessing Vortex Core (PVC) [41] is observed for both regimes inside the inner swirler stage. Wake-like structures may also be identified in the outer swirler stage. Note that based upon the second invariant of the velocity gradient tensor, the Q criterion aims at detecting coherent structures in wall-bounded turbulent flows. Q is directly related to the pressure Laplacian, \( \nabla^2 p = 2\rho \nabla \) for inviscid flows and can be interpreted as the source term of pressure in the Navier-Stokes equations. Indeed, the strong velocity gradients present near the wall prevent a clear identification of large-scale features through the use of the vorticity components. This drawback is circumvented with the help of the Q criterion as illustrated on Fig. 9.
Overall unsteady dynamics is different when considering the two axi-periodic LES predictions. The origin of the dissimilarities is highlighted by the presence of stronger pressure fluctuations at the lower regime (Point 1), Fig. 10(a), when compared to the predictions obtained for Point 2, Fig. 10(b). Note, nonetheless, that both predictions provide a similar fluctuating pressure distribution over the whole configuration. When compared to Helmholtz solver results, Fig. 2(a), the structure of the first longitudinal acoustic eigenmode is recovered by both LES results. Apparent discrepancies are localized in regions of high turbulent activity where the aerodynamic pressure field fluctuates and cannot be captured by Helmholtz solvers. The swirler and dilution holes are such elements. The longitudinal structure arises by itself in the LES which points out that mode as being potentially excited and resulting from a thermoacoustic instability. Based on the experimental observations, such a behaviour is in agreement with the engine behaviour at the first operating point. For the second regime, the longitudinal mode should not dominate contrarily to the LES prediction. However, pressure fluctuations are in LES of Point 2 much less pronounced than for Point 1 which underlines a potential geometrical constraint imposed by the axi-periodic condition.

Spectral analyses of the pressure signal recorded at various locations within the computation are presented in Fig. 11(a). Probe 1 is located inside the inner swirler stage, Probe 2 in the vicinity of the casing air inlet, Probes 3 and 4 inside the casing and Probe 5 downstream the turbine nozzle. Figure 11 compares the spectral content at both regimes as a function of the Helmholtz number $H_e = f L/c$ (where $f$ is the frequency, $L$ the casing length and $c$ stands for the mean volumetric sound speed). All probes highlight a dominating frequency, corresponding to the acoustic activity detected on each regime. Note that associated Helmholtz number of 0.3 is found regardless of the operating point, which means that they correspond to the same acoustic mode: i.e. the first longitudinal acoustic mode. The primary trend is that this acoustic mode seems to be more amplified at the lower regime, as associated amplitudes are stronger. The intense turbulent activity inside the swirler is also pointed out on Probe 1: predominant peaks are observed for very high frequencies which are associated to the PVC.

LES results suggest that the longitudinal acoustic mode dominates the overall acoustic activity at Point 1, which is in agreement with the engine operating at Point 1. Unfortunately and as expected, the single sector computational domain is not able to produce long distance azimuthal acoustic eigenmode such as the one suspected. In order to fully assess the potential of LES for the second operating point, a solution is to relax the axi-periodic condition by simulating Point 2 on the full combustion chamber as presented below.

### 4.2. Full burner LES predictions

If considering the full annular burner for LES, Fig. 12, duplications of the single sector LES predictions allow to generate a full chamber initial solution. With this strategy, initial transient is necessary for LES and the modelled physics to re-establish. During that specific phase, the simulation exhibits a clear shift in flow behaviour as reported by signals recorded by the different probes available within the computational domain.
Figure 10: Pressure fluctuations field (Root Mean Square values) obtained for (a) Point 1 and (b) Point 2.
Figure 11: Comparison between the Power Spectral Density (PSD) of the fluctuating pressure temporal signals recorded at different locations and for both operating points.

Such a change in itself constitutes valuable information and emphasizes the importance of the axi-periodic constraint on the flow prediction of Point 2. Once established and statistically stationary, LES still gives rise to a self-sustained oscillatory flow: i.e. no specific damping of the initial oscillation as found in the single sector is noted when
going to the full annular burner. The presence of the acoustic oscillation is confirmed by the visualization of the instantaneous pressure field, Fig. 13, which illustrates the presence of an azimuthal mode as evidenced by the Helmholtz solver, Fig. 2(b). A transition from a purely longitudinal acoustic mode (imposed by the replication of the single sector LES to initialize the full annular burner LES) to a purely azimuthal mode has hence happened.

It is also noted that contrarily to the single sector LES of Point 2, Fig. 10(b), the azimuthal acoustic mode present in the full annular domain is not stationary (constant position of the pressure nodes) but rotates, Fig. 13. Potential importance of non-linear phenomena that are not taken into account by the Helmholtz solver may explain the source of discrepancy between LES and Helmholtz solver predictions [34]. Mach number effects may be another explanation. Frequency analyses at one of the various probe locations, Fig. 14, however confirm that the two methods yield similar acoustic modes. Furthermore, that specific azimuthal mode is properly recovered by LES, if relaxing axi-periodicity constraint, as being the most unstable one just like the real engine.

Figure 12: Instantaneous field of temperature as obtained from the full burner LES.
Figure 13: Instantaneous pressure field provided by the full combustor LES computation (Point 2) at three successive instants.
5. CONCLUSIONS

Application of turbulent reacting Large Eddy Simulation to real burner configurations proves to be possible and reliable if used to assess the thermo-acoustic stability of a real aeronautical engine combustor. Confrontation of the LES predictions for two operating points, which are known to exhibit self-sustained pressure oscillations, against Helmholtz acoustic eigenmode solver confirms the coherence between the two approaches. While the Helmholtz solver proposes a representation of the eigenmodes potentially present in a complex configuration, LES provides diagnoses about the stability or which mode will dominate. That last statement needs however to be treated with care since proper predictions of the selfsustained limit cycle by LES still requires
to treat carefully the geometry. In the case of the first operating point simulated here, a simple axi-periodic computational domain is sufficient as the experimentally observed oscillation is known to be longitudinal. Helmholtz and LES results are for that specific operating point in good agreement. For the second operating point, the oscillation is known to be essentially azimuthal and full annular simulations are required. If possible, that last step yields coherent predictions if performed using Helmholtz solver or LES.

All of the above mentioned conclusions are valid as long as the proper volumes of the real combustion engine as mounted on the engine are covered by the computational domain. For our problem, it is noted that good numerical predictions are assured and confirm the experimental observations only if the casing, the swirler and the combustion chamber are included in the computation. Likewise, inclusion of the primary jets or any other calibrating flow section is of prime importance to properly predict the acoustic content of the system. An alternative to these extended computational domains would be to know the acoustic impedances at the boundary conditions to be applied on a reduced computational domain. Such a strategy is however not yet applicable since impedances still remain very difficult to evaluate at arbitrary locations and require major developments to be used in the context of LES. Such issues are still of importance even in the context of the present work. Indeed and despite the good agreement between the Helmholtz solver and LES, which produce similar results for the first operating point: \textit{i.e.} a longitudinal acoustic mode with $He = 0.3$, the reported experimental frequency corresponds to a value of $He = 0.15$ indicating the wrong treatment of the inlet impedance applied for both computations.

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