Identification of azimuthal modes in annular combustion chambers

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1. Motivation and objectives

This paper presents an analysis of the structure of azimuthal combustion modes developing in annular combustors. These modes pose a major danger for many industrial programs: powerful instabilities often correspond to azimuthal waves propagating in clockwise and counterclockwise directions in the annular chamber. They lead to vibrations and structural damage (Krebs *et al.* 2002; Schuermans *et al.* 2003; Lieuwen & Yang 2005). Combustion instabilities have been studied for a long time (Rayleigh 1878; Crocco 1969; Noiray *et al.* 2008; Lieuwen 2003): while most academic studies take place in simplified configurations (which were easier to study numerically and experimentally), very few address full annular chambers. The most important simplification used in experiments as well as simulations to study unstable modes in annular gas turbines is to focus on one sector only of the combustor and avoid having to work on a full annular chamber which contains typically 10 to 25 sectors. Obviously, this simplification requires some assumptions and therefore some care: the physics of instabilities in a single burner and in a full combustor with multiple burners may differ significantly. The most important difference is the existence of azimuthal modes in real annular combustors.

The physics of these azimuthal modes should not differ significantly from other, simpler configurations: the source of unstable modes in all reacting flows is the well-known flame/acoustics coupling mechanism leading to the various forms of the Rayleigh criterion (Rayleigh 1878; Poinsot & Veynante 2005; Nicoud & Poinsot 2005). In practice, however, the extension of tools used for longitudinal modes in lab-scale experiments to azimuthal modes in real combustors is not simple. The first difficulty of the study of azimuthal modes is linked to their structure (Wolf *et al.* 2010): they can appear as standing or turning (also referred to as spinning) modes and both are observed in gas turbines. Bifurcations between standing and turning modes may be due to non-linear effects. Schuermans *et al.* (2003, 2006) propose a non-linear theoretical approach showing that standing wave modes can be found at low-oscillation amplitudes but that only one turning mode is found for large-amplitude limit cycles. Other explanations are found in linear approaches: turning modes would appear only in perfectly axisymmetric configurations while any symmetry modification would lead to standing modes (Sensiau 2008; Noiray *et al.* 2010). Evesque *et al.* (2003) suggest that the initial flow conditions might trigger either standing or turning modes and Schuermans *et al.* (2006) as well as Noiray *et al.* (2011) observe that turbulence can cause random mode switching between standing and turning structures. Experimentalists also observe standing modes which have a structure that slowly rotates: the pressure nodes, for example, will turn around the chamber at a low velocity (typically a convective velocity). We will call these modes ‘rotating’ and show that they are present in our Large Eddy Simulation (LES) (Table 1).

Validating any theory or acoustic method in the framework of annular chambers remains a challenge: only a few experimental set-ups have been built in laboratories (T.U.

TABLE 1. A classification of azimuthal modes.

Type	Modes	Description
1	Standing	Pressure nodes are fixed
2	Turning or spinning	Pressure structure is turning at the sound speed
3	Rotating	Standing mode where the structure slowly rotates at the azimuthal convective speed

Munich, EM2C Paris) to study azimuthal modes in full annular chambers because multi-burner combustion chamber rigs are expensive and offer limited optical access. One method is to rely on numerical simulation: massively parallel LES, first developed for simple flames (Moin & Apte 2006; Mahesh *et al.* 2006; Schmitt *et al.* 2007; Poinsot & Veynante 2005; Selle *et al.* 2004), has been used recently for full annular chambers (Staffelbach *et al.* 2009; Wolf *et al.* 2009; Fureby 2010) despite the very high computational cost. LES relies less on modeling assumptions than our acoustic models and can predict flame/flame interactions, limit cycles, wall effects, chemical effects, etc.

The present work focuses on a partial analysis describing a LES of azimuthal modes in a realistic helicopter annular combustion chamber. The reacting unsteady flow in a full annular chamber containing fifteen sectors is computed using the exact chamber geometry, a surrogate fuel model for kerosene, a high-order numerical scheme and a fully compressible solver to track acoustic waves. It captures the self-excited azimuthal modes appearing in the real engine and provides unique insight into the behavior of the unstable combustor.

2. Numerical method and configuration

The LES solver is a fully unstructured compressible code, including species transport and variable heat capacities (Moureau *et al.* 2005; Schmitt *et al.* 2007; Gourdain *et al.* 2009). Centered spatial schemes and explicit time-advancement are used to control numerical dissipation and capture acoustics, namely the TTGC scheme (Colin & Rudgyard 2000). For the present case, a three-step Runge-Kutta method is employed with a time step controlled by the speed of sound.

Sub-grid scale viscosity ν_t is defined by the classical Smagorinsky model (Smagorinsky 1963), which reads: $\nu_t = (C_S\Delta)^2 \, ||S||$, where Δ and S are, respectively, the filter characteristic length (approximated by the cubic root of the cell volume) and the resolved strain tensor and C_S is constant (no dynamic model was used). Sub-grid thermal and molecular fluxes are modeled using an eddy diffusion assumption with constant sub-grid Prandtl (0.9) and Schmidt (0.9) numbers, respectively. Characteristic NSCBC boundary conditions (Poinsot & Lele 1992; Moureau *et al.* 2005) are used for inlets and outlets. Walls are handled with law-of-the-wall formulation (Schmitt *et al.* 2007) and multiperforated plates with an homogeneous model (Mendez & Nicoud 2008*a*,*b*). To handle flame/turbulence interactions in this partially premixed flame, the dynamically thickened flame model (TFLES) is used (Colin *et al.* 2000; Colin & Rudgyard 2000; Schmitt *et al.* 2007).

The combustion chamber contains fifteen burners (Figure 1). Each burner includes

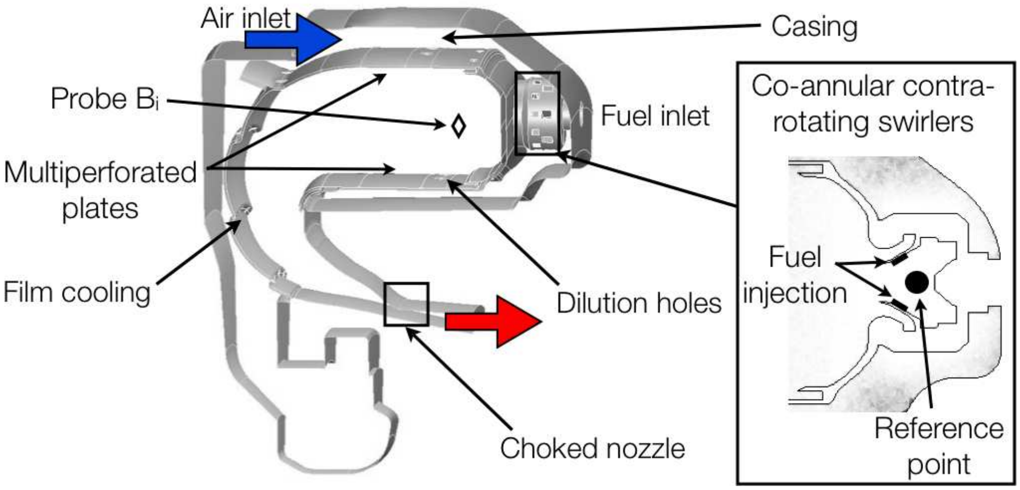

FIGURE 1. Gas turbine geometry shown on a single sector.

two co-annular swirlers. All swirlers turn in the same direction. To avoid uncertainties associated with the boundary conditions (especially on inlet and outlet impedances), the chamber casing is also computed. The computational domain starts after the inlet diffuser and ends at the throat of the high-pressure stator, which is replaced by a choked nozzle with the same minimum section, so that the flow in the outlet zone and the acoustic reflection at the throat are explicitly computed by the solver. The air and fuel inlets use non-reflective boundary conditions (Poinsot & Lele 1992). The air flowing at 578 K in the casing feeds the combustion chamber through the swirlers, cooling films and dilution holes, which are all explicitly meshed and resolved (Figure 1). Pure fuel (JP10) is injected at the swirlers' outlets through a circular slit of 2 mm width, with a velocity of 5 $m.s^{-1}$ and at 578 K (Figure 1). It is supposed to be gaseous to avoid complexities associated with atomization and evaporation. The reacting flow in the combustor of Figure 1 is simulated by first computing a single sector, duplicating the result 14 times around the turbine axis (Figure 2), and then letting the computation evolve to the most amplified oscillation mode. No forcing is added: the LES captures (or not) the oscillation modes of the combustor without any external excitation (Staffelbach *et al.* 2009).

3. LES of azimuthal unstable modes

In most cases, LES results reveal a transient period of growth followed by the development of azimuthal modes. A time-frequency analysis, based on wavelet transform (Hlawatsch & Auger 2008) (Figure 3), shows the time evolution of the frequency content of the pressure fluctuation signal measured at probe B_1 (Figure 1). At the beginning of the simulation, a frequency of 500 Hz is found and quickly vanishes, soon replaced by a frequency of 750 Hz: a longitudinal mode at 500 Hz is present in the single sector calculation and appears in the full LES before being replaced by the azimuthal mode around 750 Hz. This mode causes the flames to oscillate both azimuthally and longitudinally, creating periodic flashbacks inside the injectors (Figure 4 or animation available at elearning.cerfacs.fr/combustion/illustrations/azimut/index.php). The independency of the LES results was checked on a massively parallel system (Wolf *et al.* 2010,

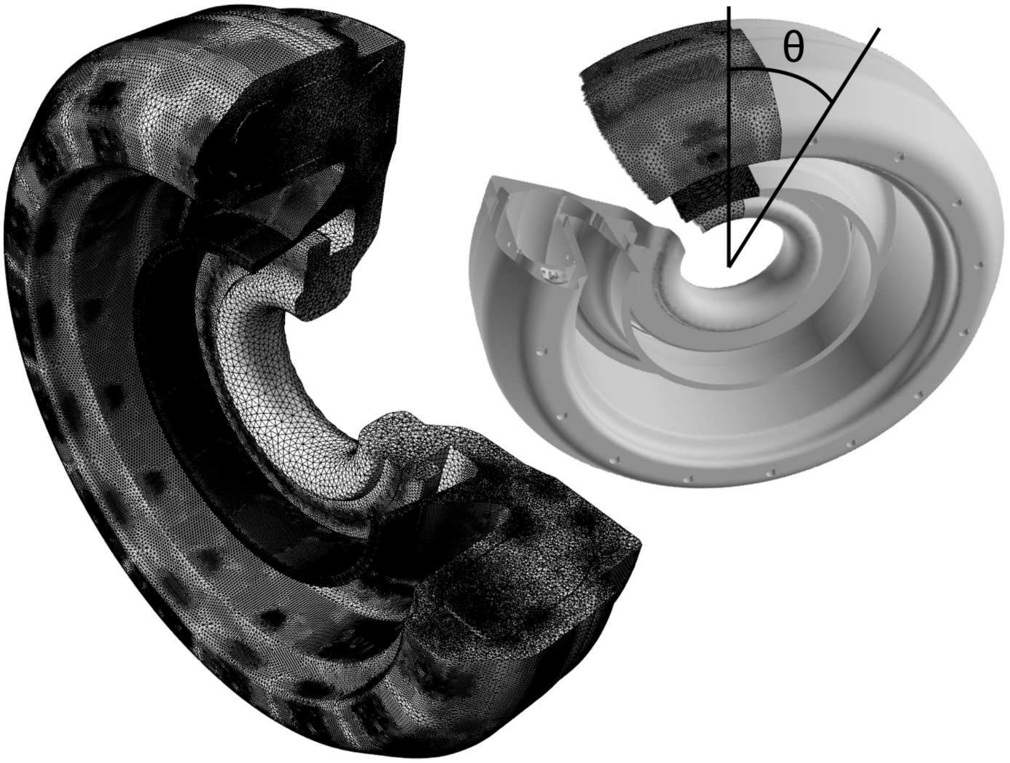

FIGURE 2. Geometry and mesh for the annular chamber.

2011) by comparing LES obtained on the three meshes with 42, 93 and 330 millions of cells. Results were very similar: the mode structure was the same, so only the 42 million cells mesh is considered here.

LES results are analyzed over a large number of cycles (100) to investigate the mode structure. The time evolution of pressure fluctuations at probe B_{12} (the B probe of Figure 1 in the 12th sector) is displayed in Figure 5: pressure oscillates at a frequency of 750 Hz. Over this sample window, a standing mode is observed and this standing mode is rotating slowly (Type 3). The rotation velocity is 44 rad/s corresponding to a mean swirl velocity $V_\theta \approx 7.8$ m/s in the combustion chamber. This value matches the azimuthal velocity levels measured in the LES.

No purely spinning mode (for which either A_+ or A_- must be zero, Type 2) is observed at this time but theoretical studies (Evesque *et al.* 2003; Schuermans *et al.* 2006; Noiray *et al.* 2011) suggest that the type of azimuthal modes could change with time. To investigate the mode nature over the whole LES duration, it is possible to use an indicator $C(t)$ proposed by Schuermans (2011). Let us consider an azimuthal mode and N evenly distributed probes along θ (Figure 6). $C(t)$ can be built as

$$C(t) = \frac{1}{N} \sum_{k=1}^{N} p_1(\theta_k, t) e^{j\theta_k} \tag{3.1}$$

where the θ_k are defined in Figure 6, using the corresponding B_i probes. $C(t)$ can be viewed as the Fourier amplitude of the first azimuthal mode.

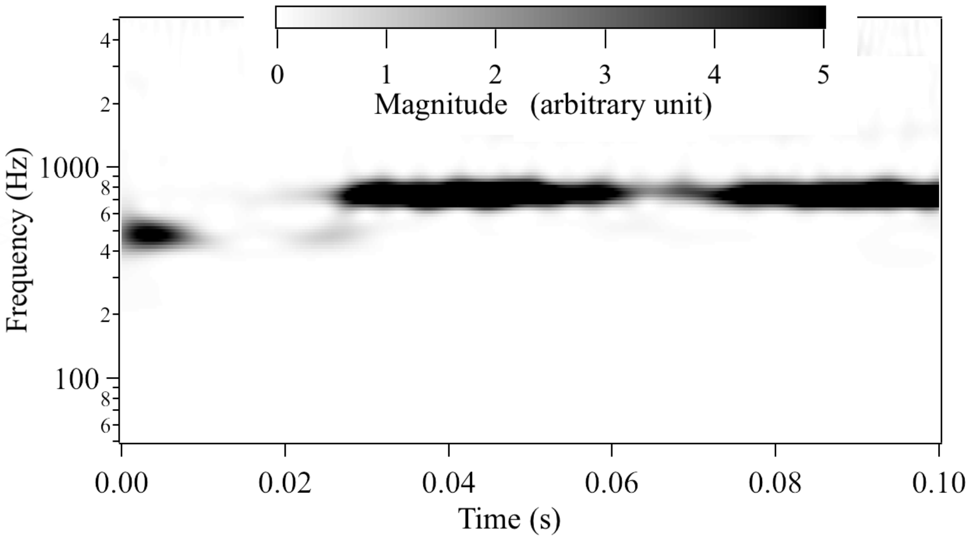

FIGURE 3. Time-frequency analysis for the pressure fluctuations measured at probe B_1 (Figure 1).

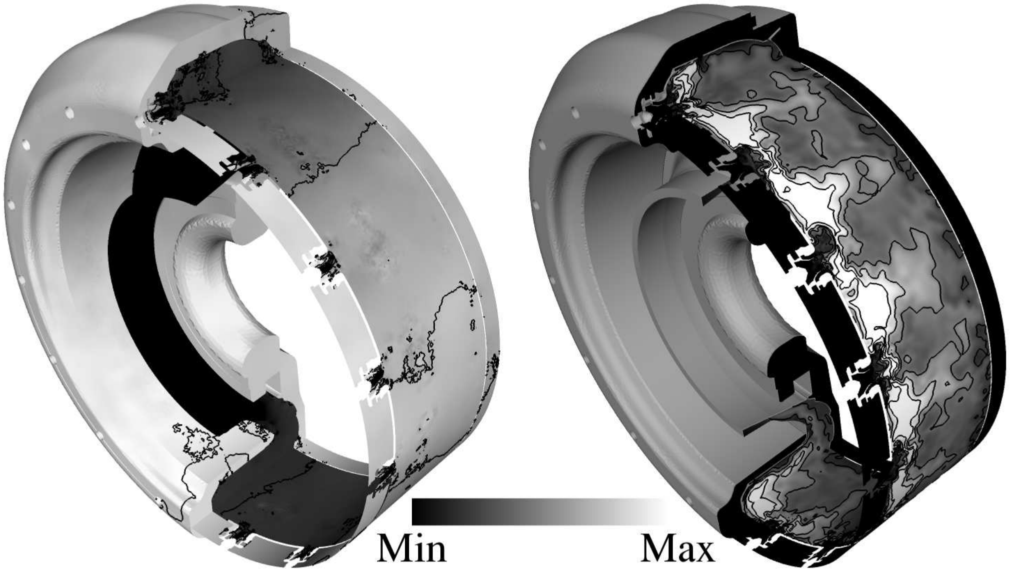

FIGURE 4. Flow visualization. Left: instantaneous pressure with pressure isocontours. Right: isocontours of temperature on a cylindrical plane passing through the B_i probes.

The $C(t)$ indicator reveals the spinning nature of the mode (Schuermans 2011): a constant indicator modulus indicates a spinning mode, whereas an oscillating indicator modulus (at a 2ω pulsation) unveils a standing mode. Moreover, the phase of the indicator is constant for a standing mode and linearly increasing (or decreasing) with time for a right (respectively left) turning mode.

The time traces of this indicator modulus (Figure 7) and phase (Figure 8) confirm the presence of a standing mode over most of the LES duration. However, a transition

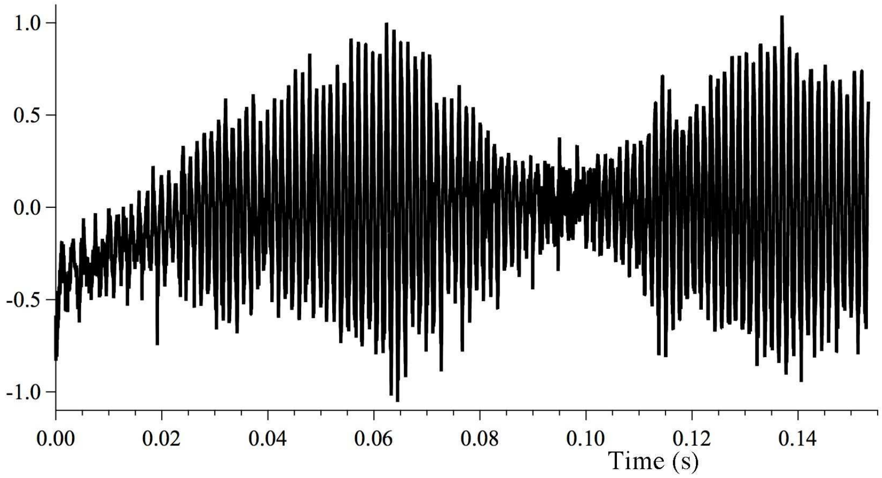

FIGURE 5. Pressure fluctuations (arbitrary units) versus time at probe B_{12}.

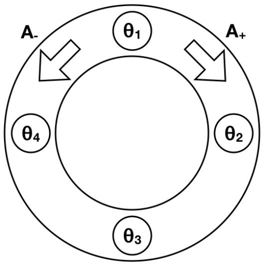

FIGURE 6. Angular location of the B_i probes to build $C(t)$, shown for 4 angular locations.

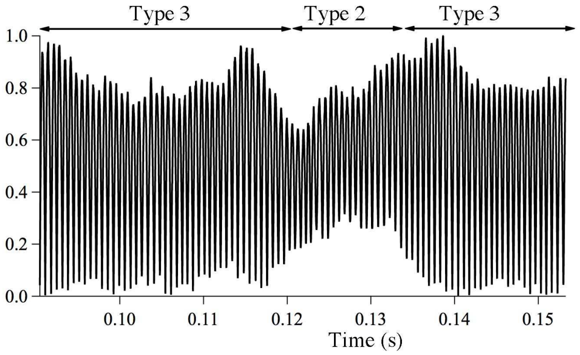

FIGURE 7. $C(t)$ indicator modulus, considering 12 evenly distributed probes.

TABLE 2. Classification of modes and corresponding C(t) indicator.

Mode type	C(t)	$\|C(t)\|$	Phase of C(t)
Standing	$A\ cos(\omega t)$	$A\|cos(\omega t)\|$	constant
Right turning	$\frac{A}{2}e^{j\omega t}$	$\frac{A}{2}$	ωt
Left turning	$\frac{A}{2}e^{-j\omega t}$	$\frac{A}{2}$	$-\omega t$

towards a mixed standing/spinning structure (Type 2) is found between 0.12 s and 0.135 s: the modulus of $C(t)$ shows reduced oscillation levels (Figure 7) while its phase clearly unwraps like $-\omega t$ during 15 ms (Figure 8), showing that A_- went to zero over this time period. It has been experimentally reported that both spinning and standing modes

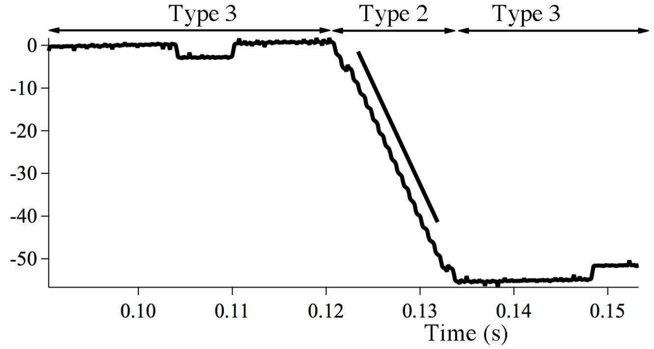

FIGURE 8. Phase of $C(t)$ indicator, considering 12 probes evenly distributed.

are observed (Hermann *et al.* 2000; Krebs *et al.* 2002; Schuermans *et al.* 2006). The present LES exhibits the same behavior. However, the underlying mechanisms driving this transition between mode types are still not clear. Evesque *et al.* (2003) observe the standing/spinning behavior of modes in an axisymmetrical annular combustor with 12 burners. Their low-order model approach (Evesque & Polifke 2002) leads them to the conclusion that the initial flow conditions might trigger either standing or spinning modes. Frequency and stability of the mode are, however, found to be independent of its spinning nature. Schuermans *et al.* (2006); Noiray *et al.* (2011) observe that turbulence can cause random mode switching between standing and turning structures. The present work supports this observation but does not provide more insight into the reasons for this mode type change.

Conclusions and future plans

The analysis of the LES of a full gas turbine annular chamber reveals that the dominant mode is a standing azimuthal mode (Type 1 in Table 1) submitting sectors located at axial velocity antinodes to strong flow oscillations and periodic flashbacks. This mode can also transition to a turning mode (Type 2) for a few cycles, and indicators of the mode nature (Table 1) show that during the 100 cycles computed with LES, approximately 20 cycles exhibit a turning (Type 2) structure while the remaining 80 cycles correspond to Type 3 (standing mode rotating at a convective velocity).

The next part of the study will focus on the possibility of modifying the chemistry in the LES simulation to look for a flame which would become stable. This would demonstrate that LES can capture both stable and unstable modes and therefore could be used at the design stage of these combustors. To reach this goal, additional tools must be used (typically Helmholtz solvers (Sensiau *et al.* 2009; Nicoud *et al.* 2007)) to predict the possible effects of chemistry changes (and flame responses) on the global flow stability.

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