Multi-Components and Multi-Physics CFD Simulations for the Prediction of Gas Turbine Flows

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Introduction

The aeronautic context

• CO₂ emissions from 1990 to 2025\(^1\): +100-600% (2008: 2.2% of the total).

• European objectives for 2020\(^2\):
  - reduce pollutant emissions (\(\text{NO}_x\): -80%, \(\text{CO}_2\): -50%),
  - reduce the noise emissions (-10dB).

• Economical constraints:
  - cut the engine costs (today it represents 30% of the aircraft cost).

Economical and environmental constraints impose technical and technological changes!

[1] INRETS, 2004
[2] ACARE recommendations
Introduction

For the specific problem of Gas Turbines

• CFD and Massively parallel computer architectures offer a clear potential for time and cost reductions

• CFD modeling needs to be specifically addressed for the three components to be simulated:
  => Compressor – RANS / URANS / LES
  => Burner – LES
  => Turbine – RANS / URANS / LES

• Each component is the locus of distinct flow physics and adding multi-physics may greatly contribute to the predictions
  => Flow separation and transition
  => Multi-phase flows
  => Chemical reaction
  => Mixing, cooling
  => Heat transfer
  …
Outline of the talk

• Massively parallel LES for the prediction of turbulent reacting flows
  ➡ Brief status on LES and the codes
  ➡ LES contributions and developments for the burner

• Thermal environment and the next generation of Gas Turbines

• Current developments to improve the engine CFD predictions of real engines

• Conclusions and perspectives
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Massively parallel LES for the prediction of turbulent reacting flows

This increase in flow and geometrical complexities is possible because of:
- the continuous increase of computing power
- code developments to ensure scalability of the solvers
Massively parallel LES for the prediction of turbulent reacting flows

LES is computer intensive!!

However and if mastered, it can be fast and make the difference for burner designs

Massively parallel LES for the prediction of turbulent reacting flows

• “Real life”: annular chambers [1-3]


• LES could provide crucial information on the development and prediction of thermo-acoustic instabilities (coupling between combustion and burner acoustic Eigen-modes)
  => threat to project since unpredictable prior full testing

• It also improves greatly design parameter predictions
Massively parallel LES for the prediction of turbulent reacting flows
Massively parallel LES for the prediction of turbulent reacting flows

A typical dimensional design parameter is the Radial Temperature Distribution Function

\[
RTDF(r) = \frac{\langle T(r,\theta) \rangle_\theta - \langle T(r,\theta) \rangle_{\theta r}}{\langle T(r,\theta) \rangle_{\theta r} - T_{\text{inlet}}} 
\]

RTDF(r) profile measures the radial temperature heterogeneities through the exit plane of the chamber ⇒ controls the turbine lifetime

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Improving the thermal environment of Gas Turbines

Improving the temperature field predictions in the burners:

=> Improve chemical processes to improve the local temperature predictions (common need if pollutants are to be also captured)

=> Heat transfer, i.e. radiation and conduction, starts to be of importance (performance of the engine)

Conduction of heat

Combustion
- Diffusion (energy, mass)
- Phase change
- Convection (natural, forced)
- Chemistry
- Acoustics

Radiation
Improving the thermal environment of Gas Turbines

Successive RDV of a parallel marching codes:

• Fluid / Radiation: timescales are such that radiation is infinitely fast

![Radiation](image1)

• Fluid / Solid: timescales are such that the flow is fast

![Solid](image2)

Statistically converged predictions
Improving the thermal environment of Gas Turbines

The main difficulties are to obtain:

1/ Easy to maintain application benefiting from individual code evolutions
2/ Interfacing massively parallel codes
3/ Taking advantage of massively parallel computers

=> non-coincident meshes, interpolation schemes, numerical stability
Improving the thermal environment of Gas Turbines

Fluid / Radiation

Fluid / Solid

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Current developments

**Extend LES for more geometrical complexity:**

The combustion chamber behavior is strongly linked to its interaction with the compressor and turbine. The inverse is also true:

- => burner thermo-acoustic response can be piloted by the acoustic response of the rotating elements.
- => turbine life-time depends on the hot streaks generated by the burner

Extend LES code to do rotating devices or go for a code-coupling solution.
Current developments

Turbine blades:

Complex flows that can not be efficiently computed with a (U)RANS method:

- laminar to turbulent transition,
- hot spot incoming from the combustion chamber,
- aero-thermal interactions (adiabatic is not true).

Arts, 1990
Current developments

- RANS predicts a non-physical shock-wave,
- URANS predicts the vortex shedding but flow features are damped by artificial viscosity,
- LES demonstrates its capacity to transport flow vortices and acoustic waves.

Current developments

- RANS predicts a non-physical shock on suction-side,
- URANS/LES correctly predict global values,
- LES estimates correctly the experimental Strouhal number.

Axial velocity registered behind the trailing edge

\[ \text{St} = f \cdot \frac{D}{U} \]

St\text{exp.} = 0.219 (-)
St\text{LES} = 0.228 (+4%)
St\text{URANS} = 0.276 (+26%)

Current developments

- T120D configuration (VKI),
- LES / Solid coupling simulation,
- Mesh is 6,5 millions of cells.

- Outlet Mach number: 0.87,
- $Re = 4.0 \times 10^5$,
- scheme: TTGC (3rd order),
- WALE turbulence model.

Duchaine, 2009

Blade

Hot flow

Plenum

Outlet

Cold flow from plenum

Aerothermal LES including plenum effects

vorticity

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An unsteady entropic wave interacts with the IGV \textit{i.e.} a hot flow region impacts the turbine blade.

Evolution of flow temperature in the turbine passage

Duchaine, 2009
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Conclusions and perspectives

Preliminary underline the feasibility of a \textit{multi-physics / multi-codes} CFD computations for aeronautical Gas Turbines:
Conclusions and perspectives

**Mathematical issues still need to be investigated:**
- convergence of the multi-code simulation (?)
- numerical stability of the multi-code scheme (?)
- …

**Other prospects can also start to be addressed…**
Thank you for your attention

Any question?
Introduction

Overview of the computational methods

RANS: Reynolds-Averaged Navier-Stokes
LES: Large Eddy Simulation
DNS: Direct Numerical Simulation