Compressible LES for Airframe noise

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Accurate noise predictions require to anticipate many flow features:

Noise radiated far away from many aeronautical devices is the consequence of many different flow regimes around the device:

Turbulence and more generally the unsteady nature of the flow will impact the frequency content and amplitude of the sound pressure level heard far away from the device

There is a clear need for an adequate evaluation / representation of these flow mechanisms

!! CFD can help !!
The physical limit of CFD: Turbulence and the large range of flow scales

Aeronautical flows have a very high Reynolds number: \[ \text{Re} = \frac{\rho U L}{\mu} \Rightarrow N \propto (0.1 \text{Re})^{9/4} \]

- **Aircraft at cruise conditions:**
  - Boeing 747, \( \text{Re} \sim 2 \times 10^9 \) => \( N \sim 4.75 \times 10^{18} \)
  - Glider, \( \text{Re} \sim 1.6 \times 10^6 \) => \( N \sim 2.8 \times 10^{11.25} \)

- **Compressor at operating conditions:**
  - \( \text{Re} \sim 5 \times 10^6 \) => \( N \sim 37 \times 10^{11.25} \)

- **Combustor at operating conditions:**
  - \( \text{Re} \sim 5 \times 10^5 \) => \( N \sim 37 \times 10^9 \)

- **Turbine at operating conditions:**
  - \( \text{Re} \sim 1 \times 10^6 \) => \( N \sim 1 \times 10^{11.25} \)
Overview of the computational methods

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

- Industrial applications
  - steady
  - unsteady (deterministic)
- Research applications
  - Unsteady (non-deterministic)

- Few hours
- Few days
- Few weeks
Introduction

Overview of the computational methods

Model → Simulation

RANS → Unsteady RANS → LES → DNS

steady → unsteady (deterministic) → unsteady (non-deterministic)

Industrial applications → Research applications

Few hours → Few days → Few weeks

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Compressible LES for Airframe noise predictions

I ] Fundamentals of LES modeling:

=> Governing Eqs and models
   - LES fundamentals and closure problem
   - SGS for free stream turbulent flows
   - Wall resolved versus Wall modeled LES

=> Numeric

III ] Compressible LES – capabilities, validations and noise predictions:

=> LES of turbulent flows
=> LES of self-sustained unstable flows (impacting jet)
=> LES based CAA on industrial like applications

IV ] Conclusions and perspectives:
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IV ] Conclusions and perspectives:
Non-linear term is the real source of our problem:

- it amplifies/redirects momentum between velocity components
- linear stability analyses give access to perturbation evolutions in simple flow (Kelvin-Helmholtz, Rayleigh…)
- in complex flows: probl for the analysis – need to linearize around something which is difficult to anticipate

Viscosity is present (as well as pressure) and introduces damping which counteracts non-linearities

Starting point of all flow description is Navier-Stokes (incompressible version):

1. Mass conservation:
   \[ \frac{\partial u_i}{\partial x_i} = 0 \] (1)

2. Momentum conservation:
   \[ \rho \frac{\partial u_i}{\partial t} + \rho u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \mu \frac{\partial^2 u_i}{\partial x_i^2} \] (2)

Reynolds number:
\[ \text{Re} = \frac{\rho u L}{\mu} \]

when $\text{Re} > 1$ Turbulence occurs

- in complex flows: probl for the analysis – need to linearize around something which is difficult to anticipate

Viscosity is present (as well as pressure) and introduces damping which counteracts non-linearities
The turbulent flow field evolves due to the competition between

**large energetic flow scales**

and

**dissipative scales**  
(i.e. mechanical energy transformed into heat)

Due to the prohibitive numerical cost of solving everything manipulations of the NS eqns need new governing eqns for which this competition needs to be modeled.
Whatever the mathematical operations applied to Navier-Stokes since the problem is non-linear, a closure problem arises

$$\langle f(x,t) \rangle_L = G \ast f(x,t) \quad G \ast \frac{\partial f}{\partial t} = \frac{\partial}{\partial t} [G \ast f], \quad G \ast \frac{\partial f}{\partial x_i} = \frac{\partial}{\partial x_i} [G \ast f], \quad G \ast 1 = 1$$ (1)

=> new unknowns appear [1-4]:

**Momentum:**

$$\tau_L(u_i, u_j) = \langle u_i u_j \rangle_L - \langle u_i \rangle_L \langle u_j \rangle_L$$ (2)

**Total energy:**

$$\tau_L(u_i, \partial p/\partial x_j)$$ (3)

$$\tau_L(u_i, u_j, u_k) = \langle u_i u_j u_k \rangle_L - \langle u_i \rangle_L \tau_L(u_j, u_k) - \langle u_j \rangle_L \tau_L(u_i, u_k)$$

$$- \langle u_k \rangle_L \tau_L(u_i, u_j) - \langle u_i \rangle_L \langle u_j \rangle_L \langle u_k \rangle_L$$ (4)


Two operators exist today:

\[ \langle f(x,t) \rangle_L = G \ast f(x,t) \]

\[ G \ast \frac{\partial f}{\partial t} = \frac{\partial}{\partial t} \langle G \ast f \rangle, \quad G \ast \frac{\partial f}{\partial x_i} = \frac{\partial}{\partial x_i} \langle G \ast f \rangle, \quad G \ast 1 = 1 \]

1/ Use an ensemble of flow realizations: \textbf{RANS / URANS}

\[ \{ u_i^{(1)}(x,t), u_i^{(2)}(x,t), \ldots, u_i^{(n)}(x,t), \ldots, u_i^{(N)}(x,t) \} \]

\[ G \ast f(x,t) = \frac{1}{N} \sum_{1}^{N} f^{(n)}(x,t) = \langle f(x,t) \rangle_L = \bar{f}(x,t) \]

\[ f'(x,t) = f(x,t) - \bar{f}(x,t) \implies \bar{f}'(x,t) = 0, \quad \bar{f}(x,t) = \bar{f}(x,t) \]
Modeling – Different formalisms => different sol. : RANS – URANS - LES

- 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.


N. Gourdain et al., in ASME Turbo-Expo, Vancouver, 2011.
Turbulence modeling is the art of providing closure / models for the above tensor

\[ \tau_L(u_i, u_j) = \langle u_i u_j \rangle_L - \langle u_i \rangle_L \langle u_j \rangle_L \]

Clearly closures will be *specific to the operator* introduced (RANS, URANS, LES…)

Clearly closures will be *specific to the flow turbulent characteristic properties*

=> need to identify typical turbulent flows and their properties

| Free stream turbulence | vs | Wall turbulence |

Fundamentals of LES modeling

\[ \tau_L(u_i, u_j) = \langle u_i u_j \rangle_L - \langle u_i \rangle_L \langle u_j \rangle_L \]

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Free stream turbulence vs Wall turbulence

If an inertial range exists, whatever the flow (homogeneous, isotropic or not), small scales (SGS quantities) can be assumed at equilibrium with the dissipation…

**Production of SGS energy**

\[ \tau_{ij} \overline{S}_{ij} \]

**Balances viscous dissipation:** \( \varepsilon_v \)

\[
\varepsilon_v \approx q_{sgs}^3 / l = q_{sgs}^3 / \Delta \\
- \tau_{ij} \overline{S}_{ij} \sim q_{sgs}^3 / \Delta
\]

=> Postulates a Gradient hypothesis and mixing length model for the turbulent viscosity

\[
\tau_{ij} \propto \nu_t \ S_{ij} \quad \text{with} \quad \nu_t \propto \Delta \ q_{SGS}
\]

\[
q_{sgs} \sim \Delta |\overline{S}| \quad |\overline{S}| = [2\overline{S}_{ij} \overline{S}_{ij}]^{1/2}
\]

Smagorinsky model (1963):

- \( \nu_T = (C_S \Delta)^2 |\mathbf{S}| \)
- Since the constant \( C_S \) (the Smagorinsky constant) is real, the model is absolutely dissipative:
  \[
  \tau_{ij} \mathbf{S}_{ij} = -(C_S \Delta)^2 |\mathbf{S}|^3 \leq 0
  \]
- To evaluate \( C_S \), assume a spectrum with an inertial range:
  \[
  E(k) = K_o \varepsilon^{2/3} k^{-5/3}
  \]
- Integrate the dissipation spectrum \( k^2 E(k) \) over all resolved wavenumbers:
  \[
  |\mathbf{S}|^2 \simeq 2 \int_0^{\pi/\Delta} k^2 E(k) dk = \frac{3}{2} K_o \varepsilon^{2/3} \left( \frac{\pi}{\Delta} \right)^{4/3}.
  \]
- With \( K_o = 1.41 \) this gives \( C_S \approx 0.18 \)

Pros & Cons:
- Purely dissipative model (no feedback to resolved scales – numerically stable ☺)
- Loss of locality (integrated spectrum)
- One constant to have dissipation and SGS?? (alignment of \( \tau_{ij} \) with \( S_{ij} \)
Recursive filtering (Germano’s identity, 1991):

Introduce two two filter scales:

\[ < U_i >_L = \int U_i(x_j - x'_j, t) G(x_j - x'_j) \, dx'_j \]
\[ < U_i >_{L'} = \int U_i(x_j - x'_j, t) G(x_j - x'_j) \, dx'_j \]

Hence double filtering sequentially with G and then by \( c_i \), you get:

\[ << U_i >_L >_{L'} = \left( << U_i >_L < U_j >_{L'} >_L \right) \]
\[ < \tau_L(U_i, U_j) >_L = \left( < U_i U_j >_L - < U_i >_L < U_j >_L \right) \]

Accessible quantities

Unclosed terms (no miracle)

For this identity, on needs to re-express:

\[ << U_i U_j >_L >_{L'} = \left( \tau_L(U_i, U_j) + < U_i >_L < U_j >_L \right) \]
\[ = \left( \tau_L(U_i, U_j) >_L + \tau_L(< U_i >_L, < U_j >_L) \right) \]
\[ + \left( < U_i >_L >_{L'} < U_j >_L \right) \]

From this relation, one obtains:

\[ \left( << U_i U_j >_L >_{L'} - < U_i >_L < U_j >_{L'} \right) \]
\[ \quad \equiv \left( \frac{\tau_L(U_i, U_j)}{T_{ij}} + \frac{\hat{\tau}_{ij}}{L_{ij}} \right) \]

### Dynamic Smagorinsky model (1991):

\[ T_{ij}^r = \hat{\tau}_{ij}^r + L_{ij} \]

Introducing the gradient diffusion model for the first two terms:

\[ T_{ij}^r = -2 (C_s \Delta_L)^2 < S_L^{ij} > \_L \]

\[ \hat{\tau}_{ij}^r = -2 (C_s \Delta_L)^2 < S_L^{ij} > \_L \] \[ < S_L^{ij} > \_L \]

so that

\[ L_{ij} = -2 (C_s \Delta_L)^2 [ < S_L^{ij} > \_L - \alpha^2 < S_L^{ij} > \_L < S_L^{ij} > \_] \]

\[ M_{ij} \]

\[ \alpha = \Delta_L / \Delta_L \]

This is an over-determined system: 1 Cst and 6 eqns (sym. tensors)…

One way to evaluate \( C_s \) is to contract the tensor: i.e.

#### Pros & Cons:

- Fully automated evaluation of the model Cst
- Potentially negative values of the coeff. (unphysical) => Need for regularization tech. (smoothing, volume average…)
- Added locality

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Turbulence modeling is the art of providing closure / models for the above tensor

\[ \tau_L(u_i, u_j) = \langle u_i u_j \rangle_L - \langle u_i \rangle_L \langle u_j \rangle_L \]

Clearly closures will be \textit{specific to the operator} introduced (RANS, URANS, LES…)

\[ \Rightarrow \text{to be discussed later on} \]

Clearly closures will be \textit{specific to the flow turbulent characteristic properties}

\[ \Rightarrow \text{need to identify typical turbulent flows and their properties} \]

Free stream turbulence vs Wall turbulence
Wall turbulence (fully developed boundary layer) is highly anisotropic:

- strong shear mean shear
- different layers are present

Region of interaction between outer BL flow and BL flow (intermittency)

Self-similar behavior of the flow

Self-similar laminar flow
From the previous findings dimensional analyses show (Piomelli 2002):

- inner layer $N_x N_y N_z \propto R_e^{1.8}$
- outer layer $N_x N_y N_z \propto R_e^{0.4}$

Two possibilities:

1/ Turbulent Re # is not too large so resolution can be sufficient (you can pay the price) but what about the SGS model?

2/ Turbulent Re # is too large; you need to model the entire wall problem…

The entire dynamics of the BL is modeled:

- Statistically stationary BL hypothesis
- Non-transitioning flow

⇒ Use of the Log-Law within the cell with inputs coming from the first off-the-wall-node

Wall law flow dynamics prevails (no pressure gradient) & the matching between turbulent SGS model and first cell wall law correction is OK…
The dynamics of the BL is simulated:

- Fully unsteady approach
- Non-transioning flow…

⇒ Constraints essentially reported on the SGS model

Works iff the SGS viscosity behaves as expected: \[ \nu_t \xrightarrow{y^+ \to 5} 0 \]
Velocity field near wall asymptotic limit yields:

\[ \nu_t \propto O(y^3) \]

Smagorinsky model:

\[ \nu_t \propto \sqrt{S_{ij} S_{ij}} \propto O(u_1) \]

!!! Impossible to use especially in the fully resolved context !!!

=> used in conjunction with a Law of the wall

WALE model\([1]\): \[ \nu_t = (C_w \Delta)^2 \frac{\left( S_{ij}^d S_{ij}^d \right)^{3/2}}{\left( S_{ij} S_{ij} \right)^{5/2} + \left( S_{ij}^d S_{ij}^d \right)^{5/4}} \]

with  \[ S_{ij} = \frac{1}{2}(g_{ij} + g_{ji}), \quad g_{ij} = \frac{\partial \tilde{u}_i}{\partial x_j}, \quad S_{ij}^d = \frac{1}{2}(g_{ik}g_{kj} + g_{jk}g_{ki}) - \frac{1}{3}g_{kl}g_{ki} \delta_{ij} \]

Yielding:

\[ S_{ij}^d S_{ij}^d \propto O(y^2) \quad \nu_t \propto O(y^3) \]

Note: denominator is here for dimensionality purposes and its form is to avoid numerical singularities!

\[ [1] \text{ F. Ducros et al., 1995.} \]
Desired properties of a ‘good’ LES model:

For proper model behavior, the filter should be applied in the lower inertial range (around Taylor micro-scale)… But one can also enforce:

1/ as $\Delta \to 0$ if the concept is well posed then LES $\to$ DNS (fully resolved problem)
   $=>$ supposes that the model contribution vanishes adequately

2/ as $\Delta \to \infty$ similarly LES $\to$ RANS (fully modeled problem)
   $=>$ supposes that the model contribution reproduces a RANS closure

Few models today can fulfill these wishes… Smagorinsky will not !!!!

How about real flows:  
- filtering and BC’s?  
- filter is rarely known,  
- transitioning flows?

...
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IV ] Conclusions and perspectives:
At some point you need to integrate numerically the modeled transport equations:

$$\frac{\partial u}{\partial t} + a \frac{\partial u}{\partial x} = \mathcal{G}(\text{cfl}, \Delta x, \frac{\partial^{2n} u}{\partial x^{2n}}, \frac{\partial^{2n+1} u}{\partial x^{2n+1}}) \quad 2n : \text{Dissipation} \quad 2n+1 : \text{Dispersion}$$

- **LES**: fully unsteady formalism where part of the turbulent spectrum activity (large scale interactions) is directly reproduced...

- **RANS**: within the context of statistically stationary flows there is no explicit need for temporal accuracy (URANS – potentially needed)

Equivalent Eqns:

**Euler explicit and centered:**

$$\mathcal{G} = \frac{a \Delta x}{2} \frac{\partial^2 u}{\partial x^2} - \frac{a (\Delta x)^2}{6} \frac{\partial^3 u}{\partial x^3}$$

**Euler implicit and centered:**

$$\mathcal{G} = \frac{a \Delta x}{2} \frac{\partial^2 u}{\partial x^2} - \frac{a (\Delta x)^2}{6} \frac{\partial^3 u}{\partial x^3}$$

**Euler explicit and upwind:**

$$\mathcal{G} = \frac{a \Delta x}{2} (1 - \nu) \frac{\partial^2 u}{\partial x^2} - \frac{a (\Delta x)^2}{6} \frac{\partial^3 u}{\partial x^3}$$

Anti-diffusion = unstable!

Numerical diffusion
The dissipation error (peak conservation): 

\[ \hat{G} \]

The dispersion error (propagation speed of info): 

\[ c^*_\varphi = \frac{\Omega^*(k)}{k} = \frac{k^*}{k} \]

Leading errors

\[ c^*_\varphi = \frac{k^*}{k} > a \]

Lagging errors

\[ c^*_\varphi = \frac{k^*}{k} < a \]

This is the region that is used for modeling and where the model is supposed to act the most to reproduced the SGS interactions needed for a proper temporal evolution of the predictions…

NOTE: Very large scales are not too affected if the scheme is centered
Gaussian convected on a 2D uniform mesh:

3D jet (H. Nguyen):

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IV ] Conclusions and perspectives:
LES around blades or airfoils

- Highly sensitive to the wall flow state
  - Transitioning Boundary Layers
- Highly compressible (Shocks)
  - Shock / Boundary Layer interactions
- Wake
  - Strong acoustic source
- Highly curved flow
  - Görtler instabilities

<table>
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<th>Test case</th>
<th>$Re_2$</th>
<th>$M_{is,2}$</th>
<th>$P_{i,0}$ (Pa)</th>
<th>$T_{s,wall}$ (K)</th>
<th>$Tu_0$</th>
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<tbody>
<tr>
<td>MUR129</td>
<td>$1.13 \times 10^6$</td>
<td>0.840</td>
<td>$1.87 \times 10^5$</td>
<td>298</td>
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<td>MUR235</td>
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<td>0.927</td>
<td>$1.85 \times 10^5$</td>
<td>301</td>
<td>6.0%</td>
</tr>
</tbody>
</table>

Heat Transfer Coeff.:

$$H = \frac{Q_{wall}}{T_\infty - T_{wall}}$$


Wall resolved LES strategy:

- elsA
  - LES structured
    - 3D fully structured multi-blocks
    - Implicit dual time integration \( O(\Delta t^2) \)
    - \( y^+ \sim 1, 2\mu m, \Delta x^+ \sim 150, \Delta z^+ \sim 25 \)
    - \( 30 \ 10^6 \) cells
    - SGS model: WALE (Nicoud, 1999)
    - Transition: cf. computation

- AVBP
  - LES unstructured
    - 3D fully unstructured
    - Explicit time - Taylor Galerkin \( O(\Delta t^3) \)
    - \( y^+ \sim 4, 8\mu m, \Delta x^+ \sim 4\Delta y^+, \Delta z^+ \sim 4\Delta y^+ \)
    - \( 30 \ 10^6 \) cells
    - SGS model: WALE (Nicoud, 1999)
    - Transition: cf. computation

1/ Capabilities of the two LES numerical strategies to produce coherent flow predictions

2/ Numeric and code efficiencies

\[ \Rightarrow \text{Robustness of wall resolved LES to turbulent BL state sensitivity of the flow} \]
LES around blades or airfoils

LEs structured

1: Laminar flow
2: Impacting acoustic waves
3: Transition

LES unstructured

- Instantaneous field of the wall heat flux \( Q \) (W.cm\(^{-2}\))
- Transition occurs at S=60mm
- Transition is initiated by a sonic point

LES around blades or airfoils

1: Incoming turbulence impacting the blade leading edge
2: Turbulent spots
3: Stretched vortices (Görtler)

- Instantaneous field of the wall heat flux $Q$ (W.cm$^{-2}$)
- Transition seems to be of «by-pass» type
- Appears between $S=40$mm & $S=60$mm
- Interaction between the shock and the transitionned turbulent boundary layer

LES around blades or airfoils

- **Pressure side:** H under estimated by less 5%
- **From S=-20 to S=50mm:** Both LES provides prediction with a 5% error (cf. exp.)
- **After transition:** elsA under estimate by 25%, AVBP by 40%

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**LES of turbulent wall impacting jets**

**Under-expanded impacting jet (Mach bottle):** depending on h/d and Nozzle Pressure Ratio (NPR), stable or unstable flow can appear…[1]

- Stable case to validate modeling *(wall modeled LES)*, grid resolution… [2]
- Unstable case to see if LES captures the acoustic loop [3]

---


<table>
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<th>Time step</th>
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</table>
Acoustic pressure field:

Resolution (i.e. Energy containing structures) does impact SPL predictions:

1/ Overall flow topology (mean field) does not seem so sensitive
2/ Unsteady features are however critical for good SPL results… Only a good resolution allows a somewhat grid independent result (increasing further does not change the freq. content of the SPL)
Change of operating condition: NPR = 4, h/d = 4.16 => 2.08 (A. Dauplain et al., AIAAJ, 2011)
Acoustic field – validation of the limit-cycle:

Careful use of LES allows proper flow sensitivity capturing:

1/ Here wall modeling does not seem to be crucial
2/ Grid resolution is of prime order
   => quid of the SGS modeling?
   => quid of numeric (only high order scheme worked)

=> identical treatments to remove any uncertainty in the treatment

Overall recommendations on the modeling and validation strategies:

Validations of LES codes is not an obvious because you end up handling a fully dynamic system expressing interactions between:

- numeric
- SGS model
- grid resolution (structured vs unstructured)
...

Basic test cases are necessary and assessment of your modeling strategy needs to be faced to well mastered configurations where flow data (unsteady and mean) are available…
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IV ] Conclusions and perspectives:
Prediction of the sources is one thing, propagating them is another thing...

Most LES numerical scheme introduces too much dissipation & dispersion to preserve and propagate accurately the small amplitude pressure fluctuations over a long distance… LES needs to be coupled to another acoustic solver

=> CAA (Computational Aero-Acoustic)

Questions to be answered:
- What other code? Linearized Euler, Acoustic Analogy…
- What quantity to transfer?
- Where to extract the info?

1/ Broadband noise: free jets
2/ Tone dominated noise: rod-airfoil interaction
Classical benchmark [1]: J.-C. Giret et al. (CIFRE CERFACS / AIRBUS)

- Rod vortex shedding at St ~ 0.19
- Turbulence in the cylinder wake

=> Impingement of the shedded vortices on the airfoil generates the tone
=> turbulent containing wake generates the broadband noise

Mean flow prediction validations:

Wall resolved LES: i.e. WALE and initial guess for the first layer $y^+$

=>$\text{Cylinder BL is fully transitioning with a massive separation around } +/-90^\circ$
• Closer observations:
  => Quadrupolar noise emitted from small structure in the turbulent wake of the rod
PSD @ 90°

- Exp.
- AVBP Coarse Mesh
- AVBP Fine Mesh

LES based CAA
Preliminary conclusions for LES based CAA:

Wall modeling is crucial: not only does it impact the flow topology but by doing so, it will also impact the acoustic source locations and sound propagation.

**Note:** For tone dominated flows, the intensity of the sources may not be so much affected…
Industrial applications

**LAGOON database**: J.-C. Giret et al. (CIFRE CERFACS / AIRBUS)

- Benchmark CFD/CAA codes
  - Aerodynamic measurements (F2 wind tunnel)
  - Far-field acoustic measurements (Cepra 19 wind tunnel)
- Several operating points (Mach number 0.18 and 0.23)
- **3 geometries** with increasing geometrical complexity

Codes: ElsA, SotonCAA, Openfoam, TAU, Powerflow
• Geometry #1 selected at first a Mach number 0.23
  ▸ $T_\text{in}=293\,\text{K}$
  ▸ $V_\text{in}=78.8\,\text{m/s}$
  ▸ $P_\text{in}=99400\,\text{Pa}$

• Full geometry with support considered
  ➢ CEPRA 19 design
  ➢ No acoustic reflection from the ceiling

• 3 levels of refinement investigated
  ➢ Coarse: 10 million cells
  ➢ Fine: 50 million cells (global refinement of the mesh)
  ➢ Very fine: 75 million cells (additional refinement at the LG walls)
Coarse full tetra mesh

Coarse mesh with prism layers
**Fixed numerical scheme:**
- TTG4A Scheme (Third order in space and Fourth order in time)
- Explicit time marching, CFL=0.7

<table>
<thead>
<tr>
<th>Casename</th>
<th>DoF</th>
<th>dt</th>
<th>CPU time (for 0.24 s)</th>
<th>Wall-law</th>
<th>SGS Model</th>
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<tr>
<td>FINE_DS_WNS</td>
<td>10 M nodes (50 M cells)</td>
<td>4.10^{-7} s</td>
<td>100 000 h</td>
<td>NO</td>
<td>DSMAGO</td>
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<tr>
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<td>15 M nodes (75 M cells)</td>
<td>3.10^{-7} s</td>
<td>200 000 h</td>
<td>NO</td>
<td>DSMAGO</td>
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<tr>
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<td>VERYFINE_DS_WL</td>
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<td>3.10^{-7} s</td>
<td>200 000 h</td>
<td>YES</td>
<td>DSMAGO</td>
</tr>
</tbody>
</table>
No spurious reflections at the ceiling
-> in accordance with C19 design
Best agreement obtained on VERYFINE Mesh with DSMAGO model with and without wall laws
Industrial applications

Detailed comparison with LAGOON to be produced

Preliminary conclusions:

Extreme care needs to be taken when attempting LES based CAA

=> LES modeling (and numeric) will impact drastically the quality of the predictions
=> the acoustic treatment and model / analogy will also affect the results
• **Geometry #2**: added complexity (torque link)

<table>
<thead>
<tr>
<th>Casename</th>
<th>DoF</th>
<th>dt</th>
<th>T</th>
<th>CPU time</th>
</tr>
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<tbody>
<tr>
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<td>22M nodes (110M Elements)</td>
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<td>24M nodes (120M Elements)</td>
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<td>0.12s</td>
<td>~200 000 H Cpu</td>
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Axial component of the velocity vector

PIV

VERYFINE#3_DS_WNS
Other ongoing industry-like applications

1/ production of VALIANT EU Project & partners:

2/ Bodart et al. (Stanford):

3/ Thiele et al. (DLR):

4/ Jet noise by ECL and Stanford:

Compressible LES for Airframe noise predictions

I ] Fundamentals of LES modeling:

=> Governing Eqs and models
   - LES fundamentals and closure problem
   - SGS for free stream turbulent flows
   - Wall resolved versus Wall modeled LES

=> Numeric

III ] Compressible LES – capabilities, validations and noise predictions:

=> LES of turbulent flows
=> LES of self-sustained unstable flows (impacting jet)
=> LES based CAA on industrial like applications

IV ] Conclusions and perspectives:
Conclusions and perspectives

LES based CAA offers:

- Good potential for flow unsteadiness predictions (better representation of the acoustic sources)

- Tone generated noise is a priori the easiest to reproduce

GOOD NEWS

=> Modeling will dominate and will do the difference

Not only on the LES side (SGS, wall…) but also on the acoustic side.

=> Numeric and massively parallel codes will be required

Note: Acoustic BC’s need to treated with care for proper representation
Where do we stand on the LES side:

Today codes are able to produce computations using $O(10^3-10^5)$ cores **efficiently**:

- 1 Million cores LES simulation for Aero-acoustic predictions
- Allowing simulating fully transient phases over few ms