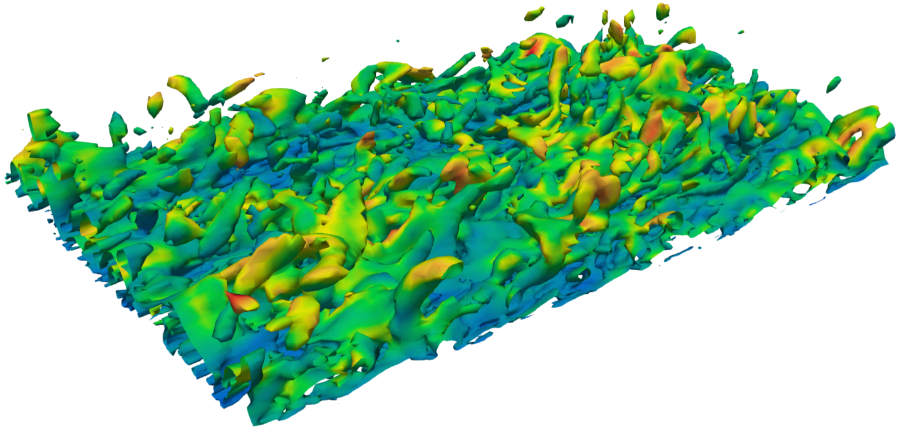
Progress in high-order large-eddy simulation of aeronautical flows using the integral-length scale approximation turbulence model

B. Font*, S. Pezzano, F. Naddei, M. Montagnac, O. Lehmkuhl



HiFiLeD Symposium 2022

Barcelona Supercomputing Center
Centro Nacional de Supercomputación
ONERA
THE FRENCH AEROSPACE LAB

NextSim
Next generation of industrial aerodynamic simulation code
EuroHPC Joint Undertaking

Discretization methods, turbulence models, and mesh types, affect convergence

Spatial discretization methods:

- Finite Difference
- Finite Volume
- Finite Element
- Discontinuous Galerkin

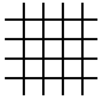
....

LES turbulence closures:

- Smagorinsky
- Dynamic Smagorinsky
- WALE (wall-adapting local eddy-viscosity)
- Vreman

...

Mesh



- There is no obvious choice to match discretization method and turbulence model.
- Turbulence models usually are case- (and mesh-) dependent too.

$$\tau_{ij}^a = -2\nu_{\text{SFS}}\bar{S}_{ij}$$

$$\phi = \langle\phi\rangle + \phi'$$

The integral length scale approximation (ILSA) model

The filter width $\triangle$ depends on an estimated integral scale, and not on the local cell size.
The integral scale is calculated with temporal-averaged quantities.

$$\nu_{\text{SFS}} = (C_k L_{\text{est}})^2 \left|\bar{S}\right| \qquad \triangle = C_\triangle L_{\text{est}} \qquad L_{\text{est}} = \frac{\langle\mathcal{K}_{\text{res}}\rangle^{3/2}}{\langle\varepsilon_{\text{tot}}\rangle}$$

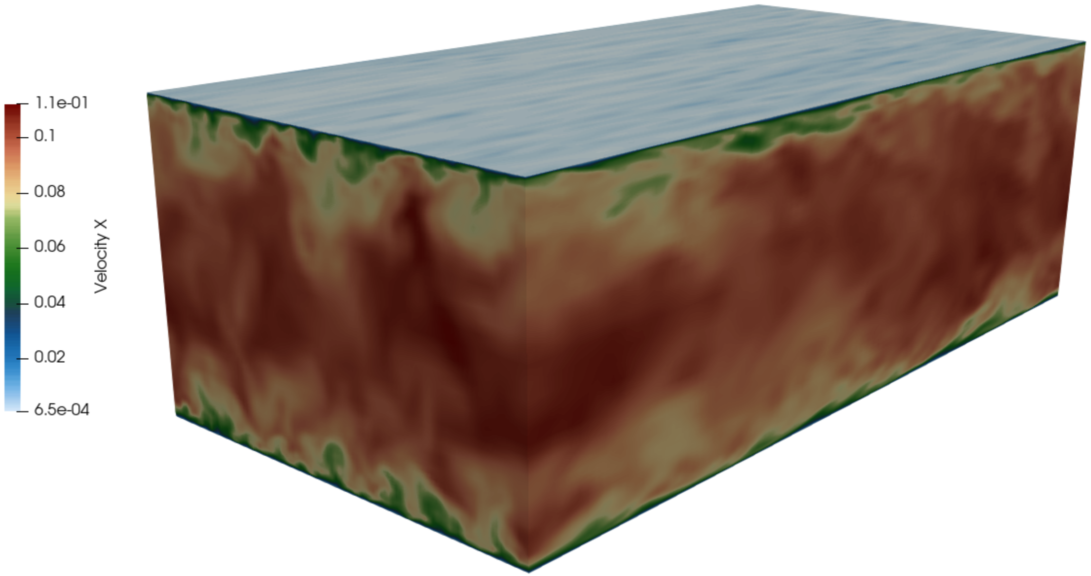
C_k is determined via s_τ, ILSA's single parameter which encapsulates the amount of turbulent kinetic energy aimed to be modelled.

$$s_\tau = \left[\frac{\langle\tau_{ij}^a\tau_{ij}^a\rangle}{\langle(\tau_{mn}^a + R_{mn}^a)(\tau_{mn}^a + R_{mn}^a)\rangle}\right]^{1/2} \qquad \mathcal{X}_1[1-(1/s_\tau)^2]C_k^4 - \mathcal{X}_2 C_k^2 + \mathcal{X}_3 = 0$$

- Because mesh independence, ILSA yields grid converged results for a range of s_τ .
- Suitable for h-adaptivity, and p-adaptivity in high-order methods.

1. A. Rouhi, and U. Piomelli, 2016. Phys. Rev. Fluids 1, 044401.
2. O. Lehmkuhl, U Piomelli, and G Houzeaux, 2019. Int. J. Heat and Fluid Flow.

Turbulent channel flow at $Re_\tau = 950$



Geometry: $6h \times 2h \times 3h$

$Ma = 0.08$

BC: Top & bottom walls: no-slip.
Others: periodic.

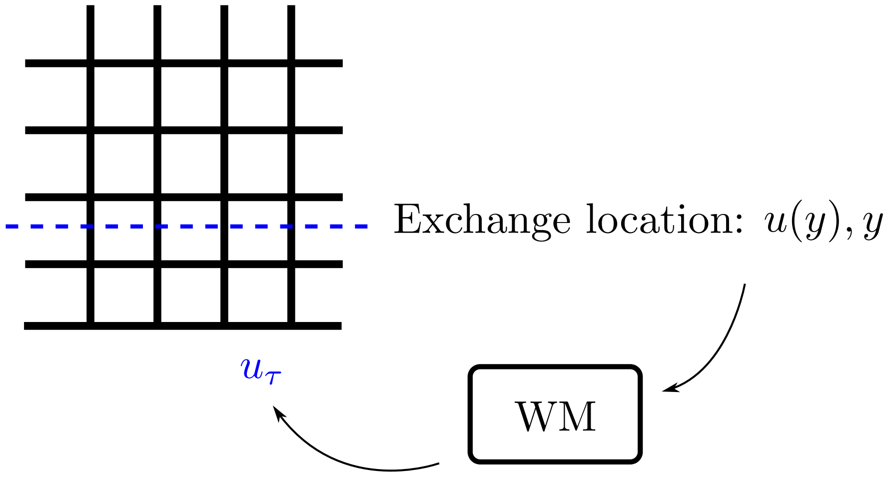
IC: Perturbed analytical solution.

Statistics averaged for $100\,T$.

Mesh WMLES (DOFs): $54 \times 62 \times 54$
$y^+ = 100$

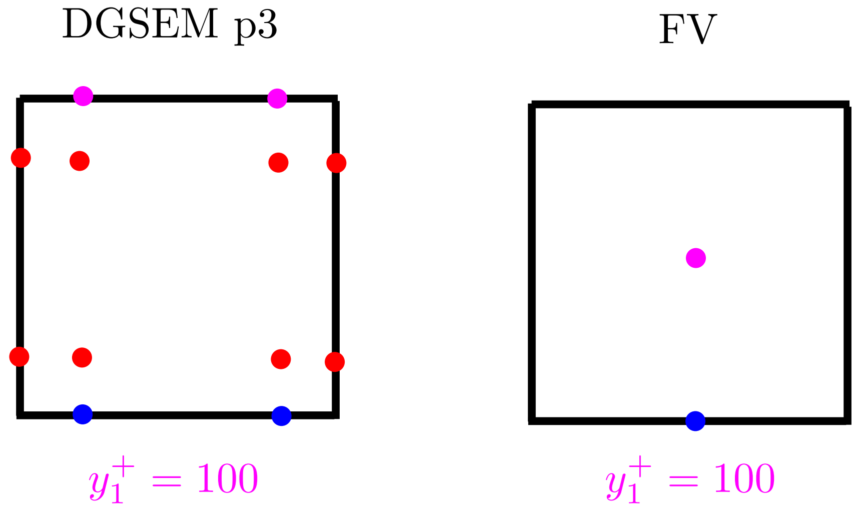
Numerical methods: a) DGSEM p3, SLAU2 convective scheme, RK4 time scheme, equilibrium wall model
b) FV, Kok convective scheme, RK4 time scheme, equilibrium wall model

Equilibrium wall model implementation

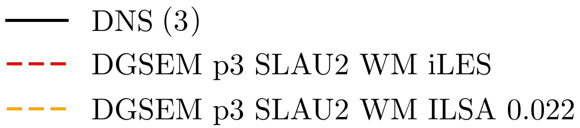


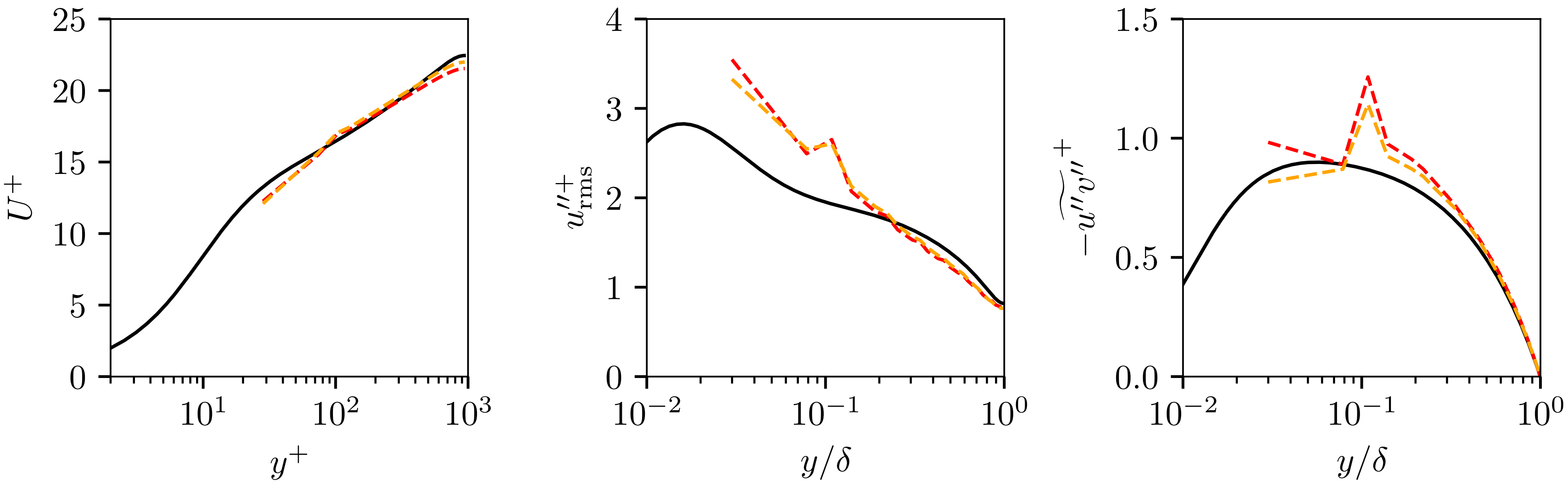
Wall model (WM):

$$\frac{u(y)}{u_\tau} = \frac{1}{k}\ln\left(\frac{u_\tau y}{\nu}\right) + B$$



DGSEM converged profiles for 100T

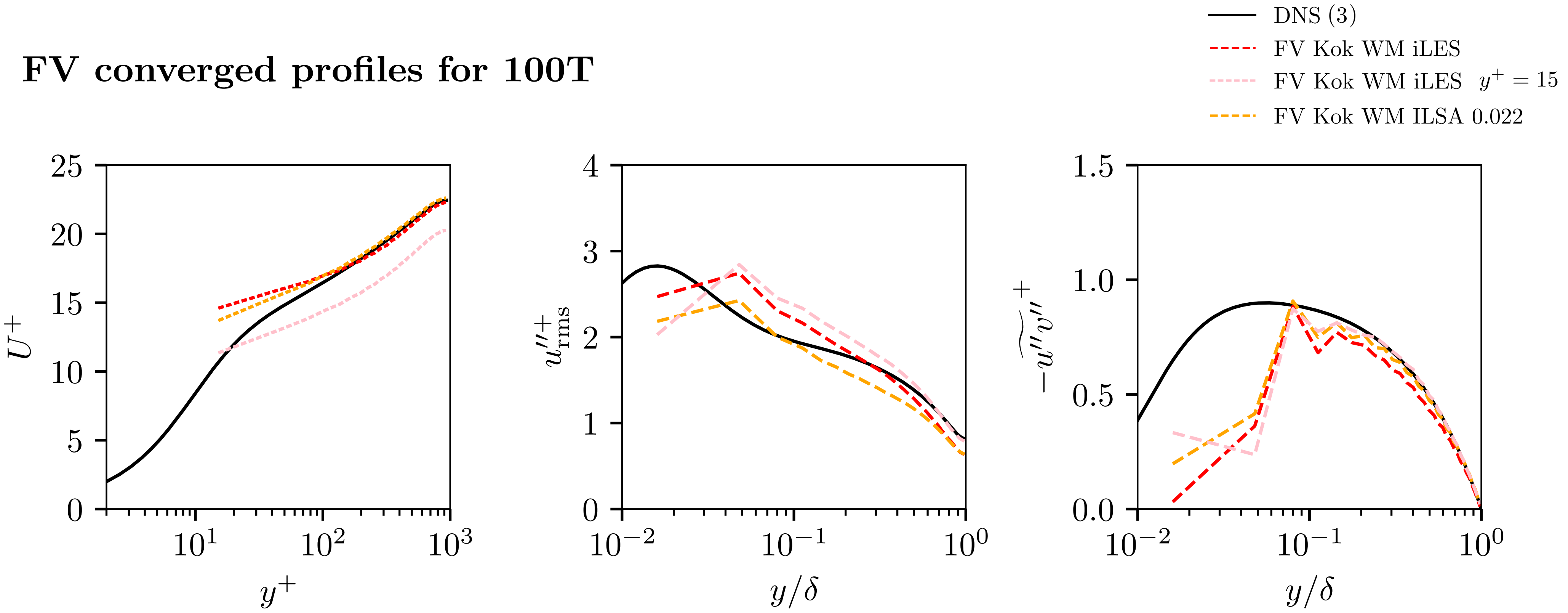




- Good agreement above $y^+ = 100$
- ILSA slightly improves the mean profile and the fluctiations.

3. Hoyas & Jimenez, 2008. Phys. Fluids 20, 101511

FV converged profiles for 100T

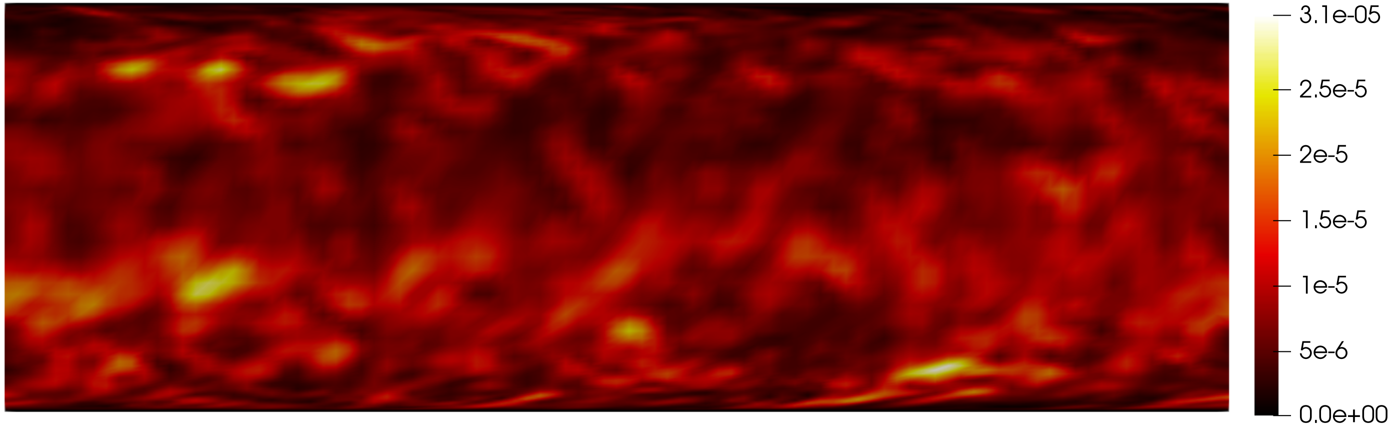


- Log-layer missmatch when using $y^+ = 15$ exchange location
- Good agreement above $y^+ = 100$
- ILSA slightly improves the mean profile and the fluctuations.

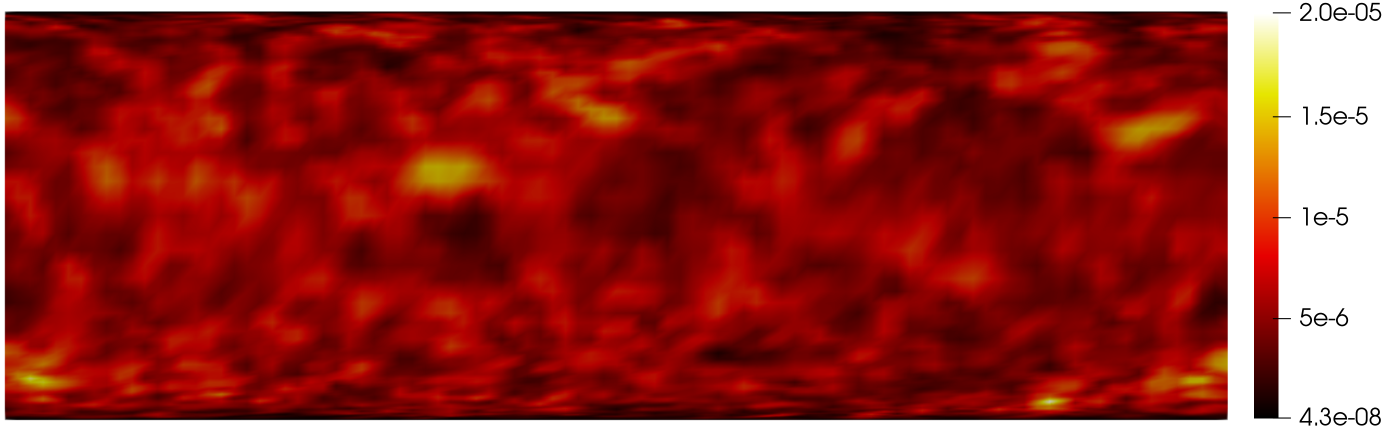
3. Hoyas & Jimenez, 2008. Phys. Fluids 20, 101511

The ILSA SGS viscosity follows physical structures in an anisotropic WRLES mesh

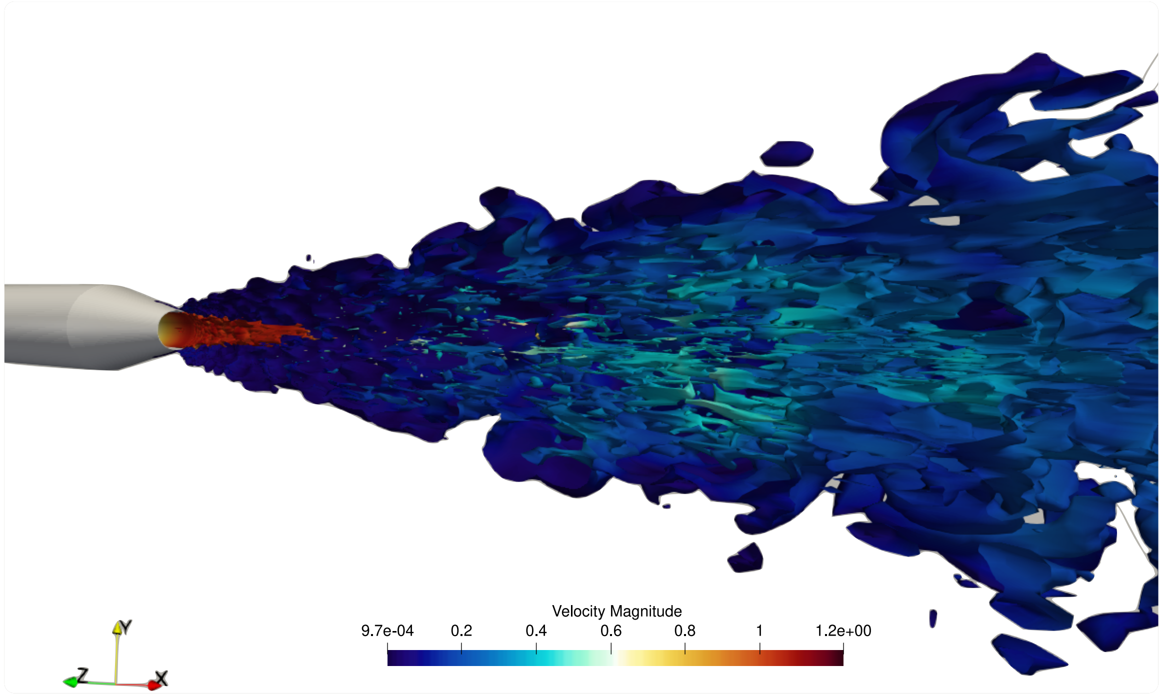
ILSA
$s_\tau = 0.022$



Vreman
$c \approx 2.5C_s^2 = 0.07$



Jet exhaust aerodynamics and noise (JEAN)* test case



$Re = 10^6$

$Ma = 0.9$

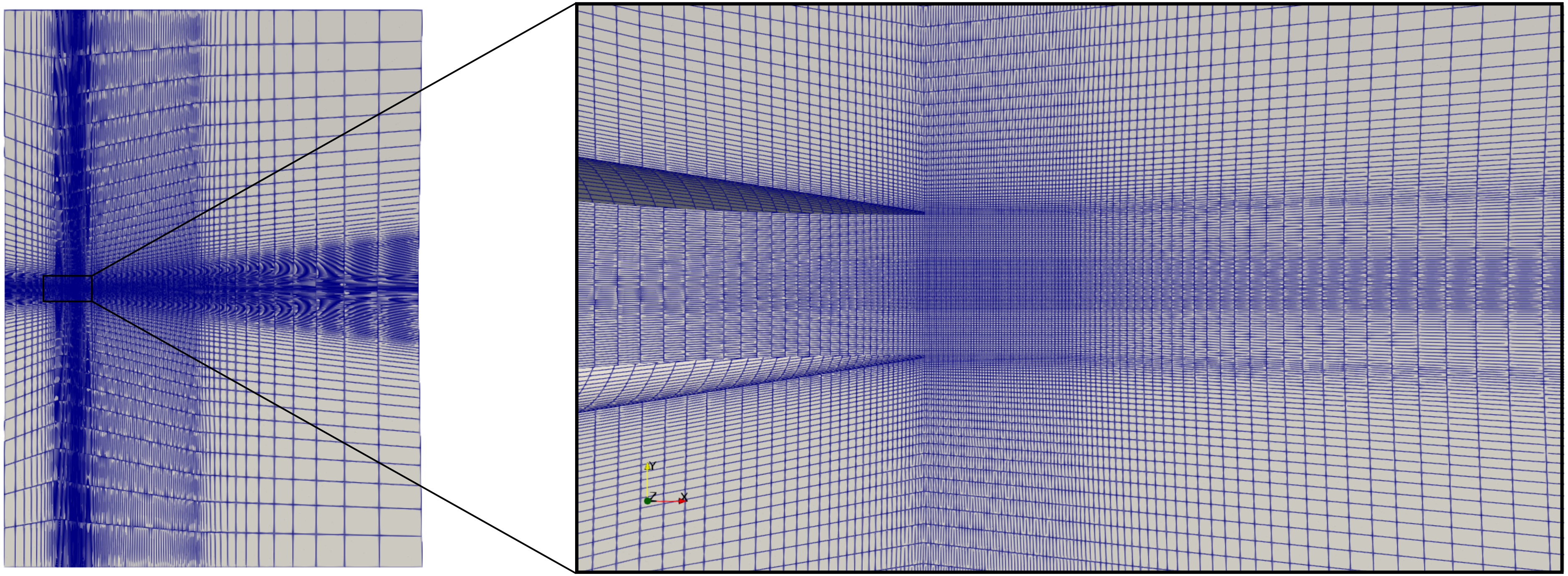
IC: RANS-SA using FV + p staging

Linear WM mesh: 138M DOFs (2.1M Hex64)
HO WM mesh: 130M DOFs (2.0M Hex64)

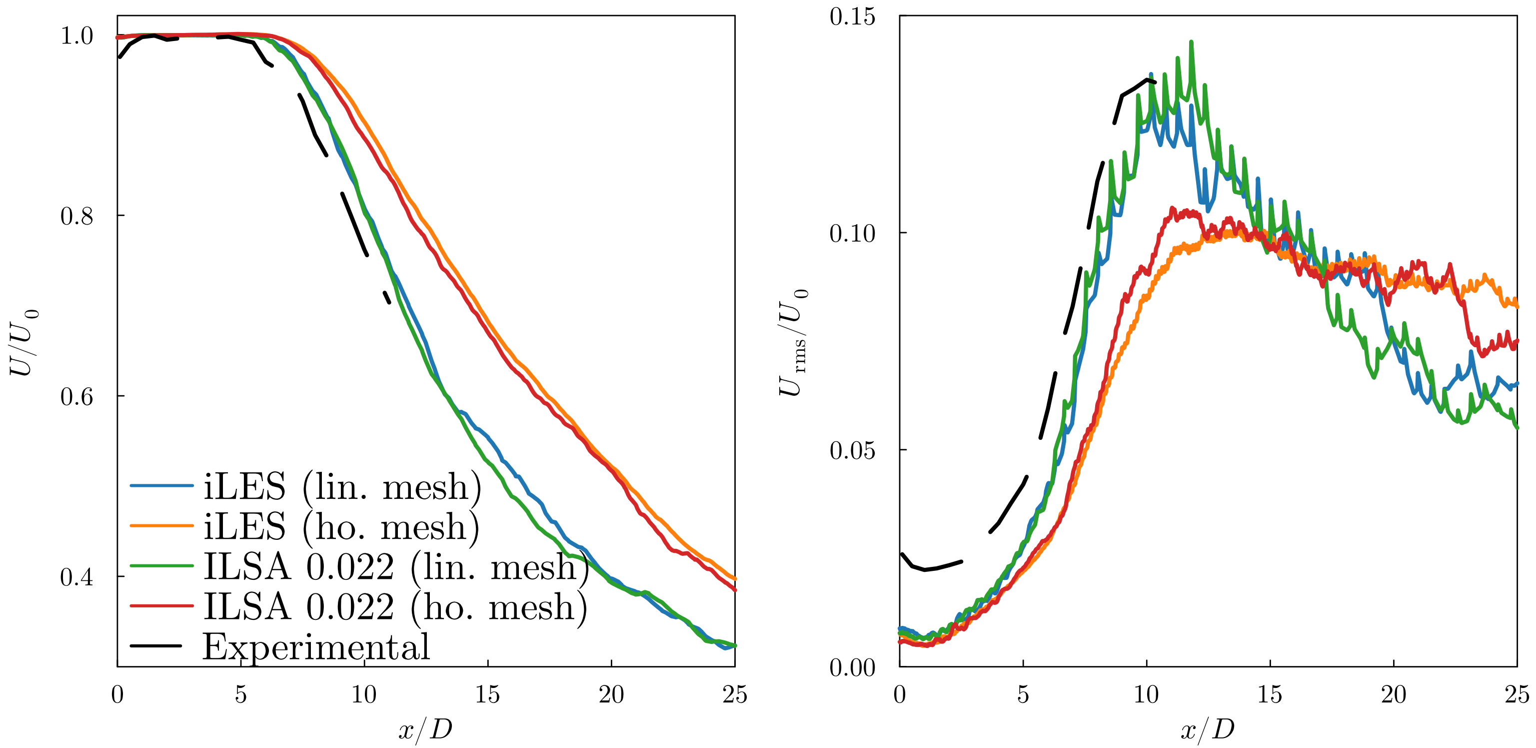
Numerical methods:
- DGSEM p=3
- SLAU2 convective scheme
- RK3 time scheme
- Equilibrium wall model

* https://cordis.europa.eu/project/id/G4RD-CT-2000-00313

A highly anisotropic mesh can be challenging for turbulence models

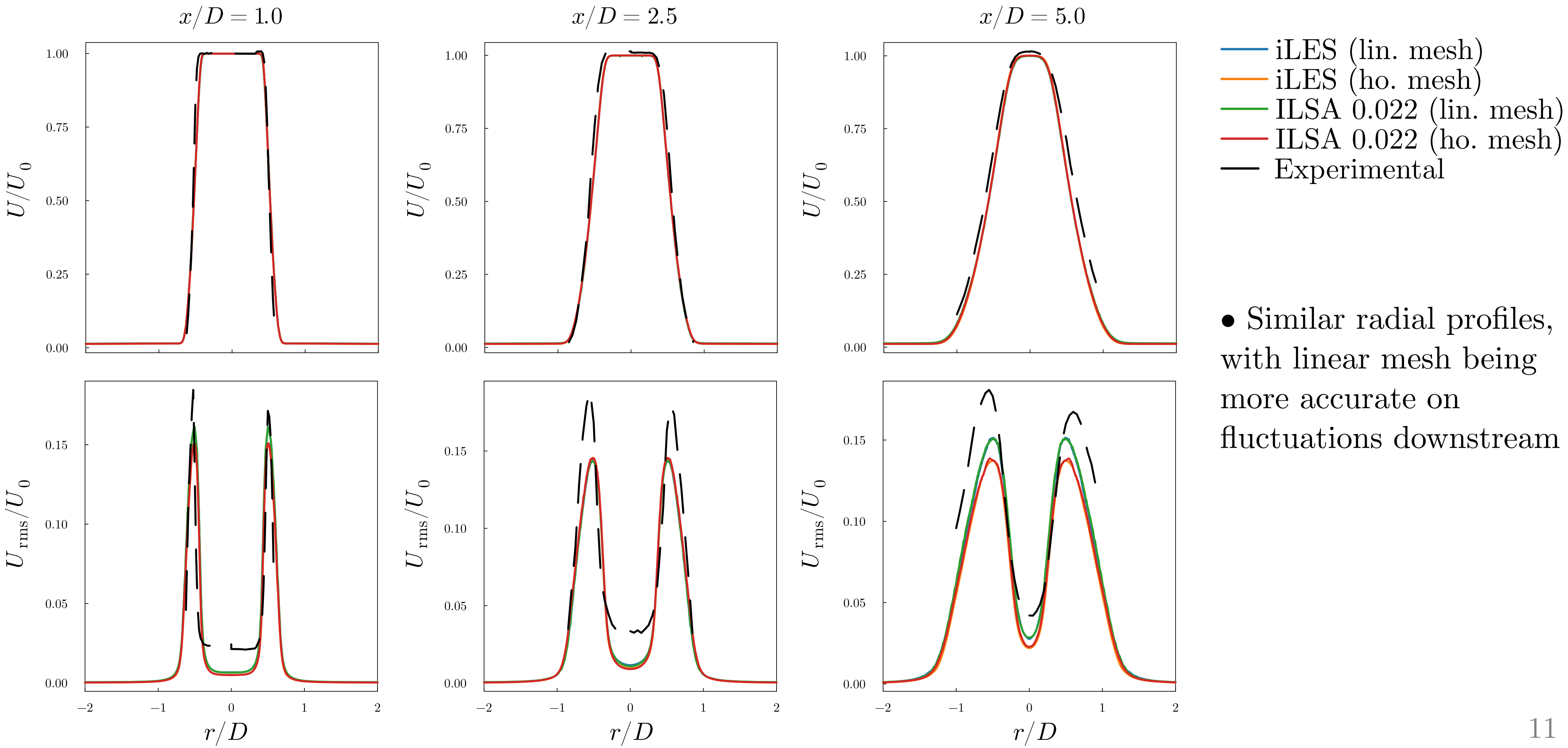


Jet aerodynamics comparison for iLES/ILSA and linear/high-order mesh



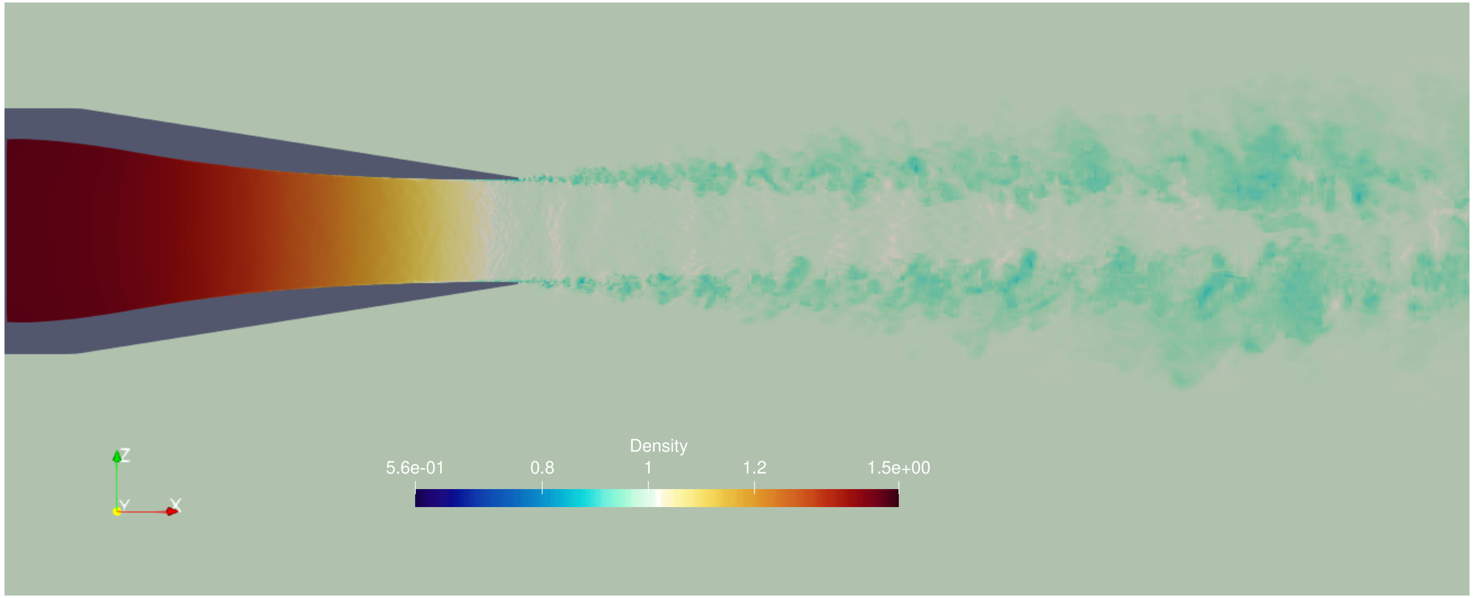
- Linear mesh provides a better general trend, but is more noisy.
- HO mesh mitigates the noise, but more dissipation appears.
- ILSA slightly improves the profiles for both mesh cases.

Jet aerodynamics comparison for iLES/ILSA and linear/high-order mesh



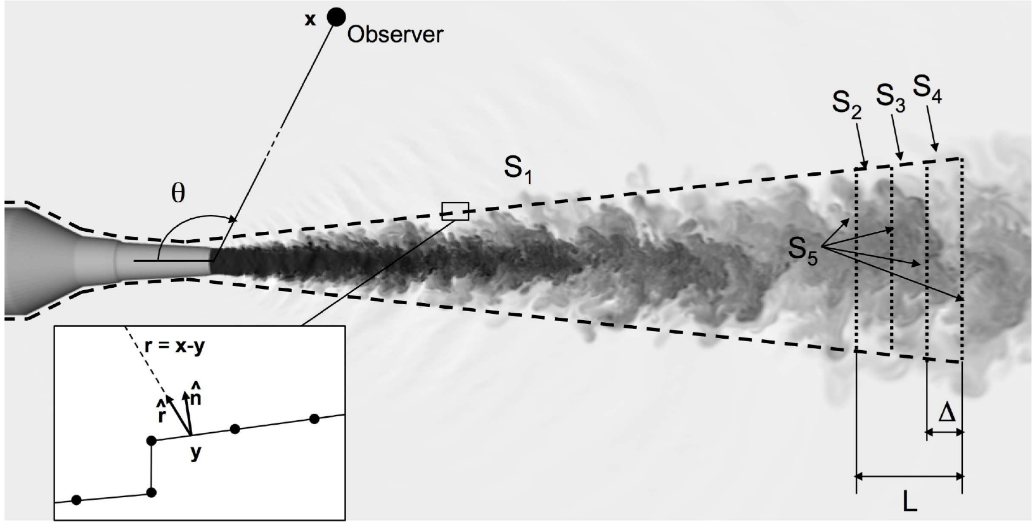
- Similar radial profiles, with linear mesh being more accurate on fluctuations downstream

Tripping or a turbulent inlet condition might be necessary...



- If no wall model is used, unphysical artifacts can develop inside the nozzle.
- Adding an equilibrium wall model yields laminar flow inside the nozzle hence impacting the jet exit
- Boundary-layer tripping or turbulent inlet might improve the nozzle oulet flow state.

Acoustic analysis comparison for iLES/ILSA on the high-order mesh



Mendez et al., 2013. Int J. Aeroacoustics 12, 1-20

• Far-field sound calculated through the Ffowcs Williams-Hawkings (FWH) equations.

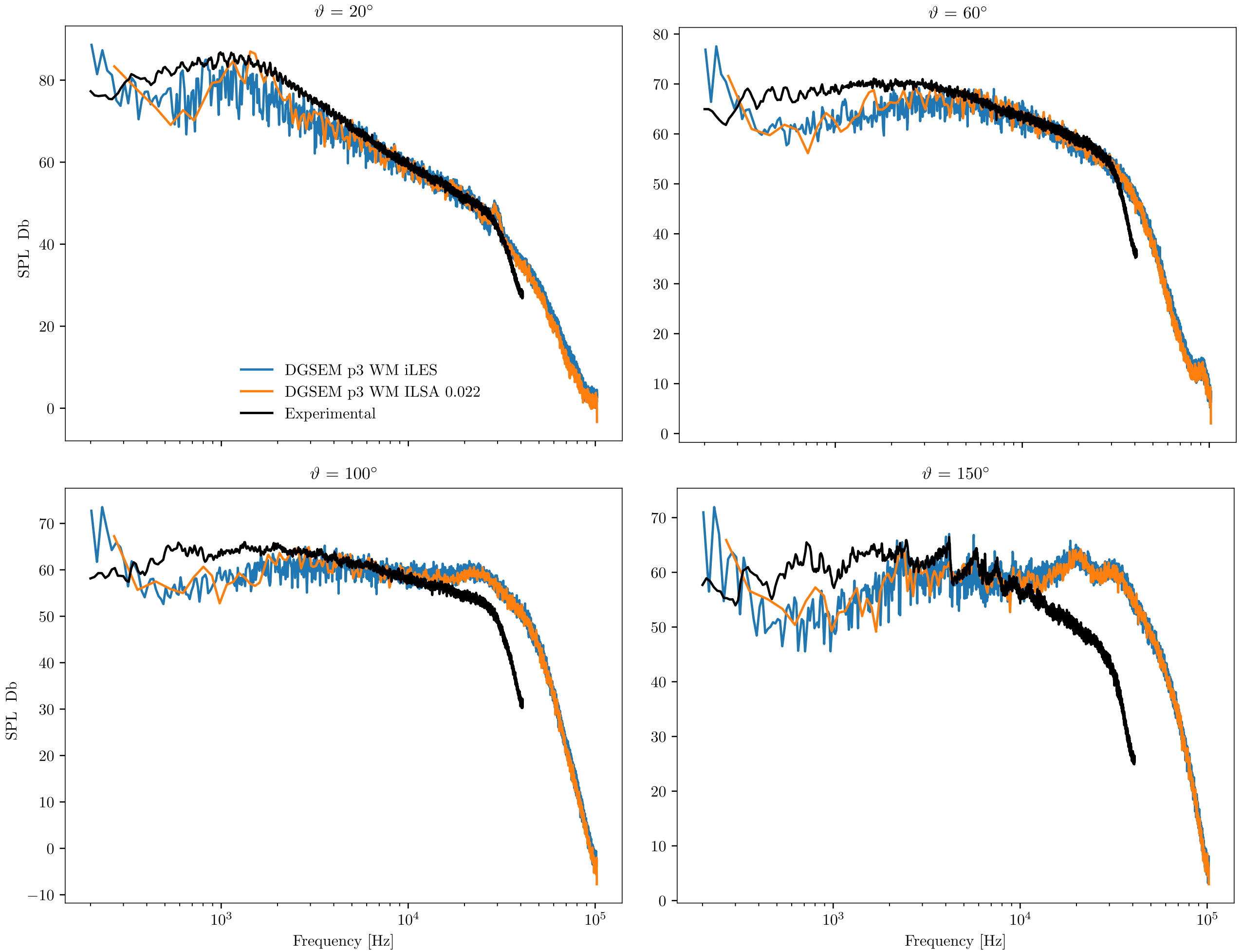
1) Flow state (U) temporal evolution saved over S at frequency f during T time.

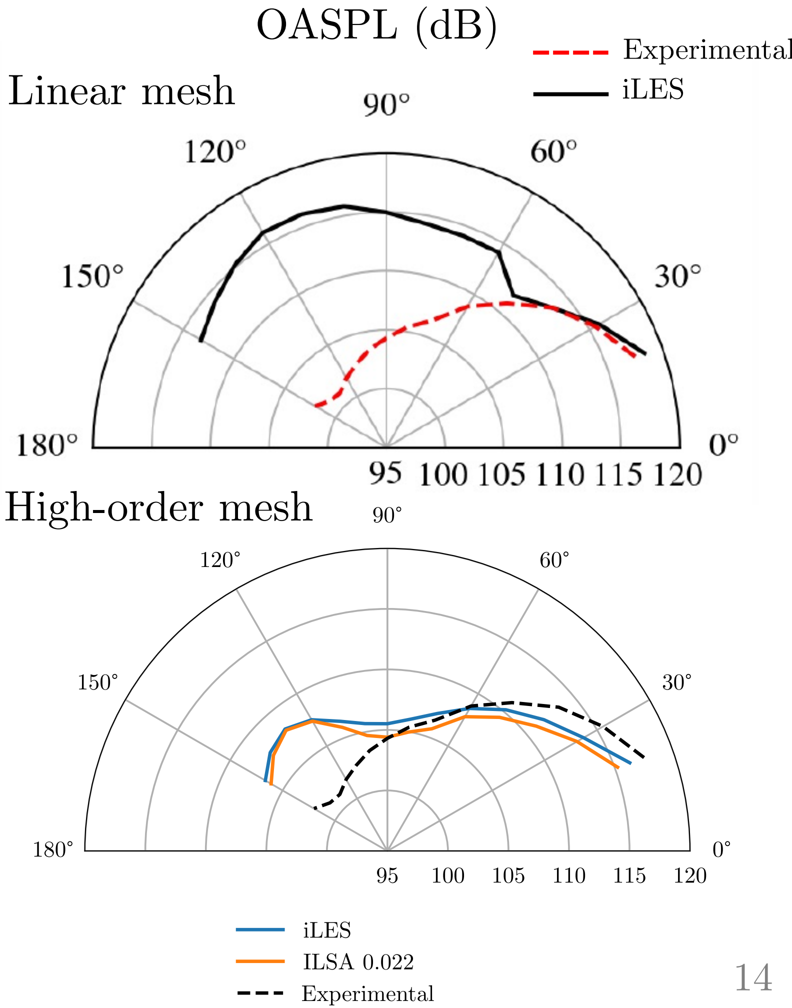
2) Compute the pressure fluctuating source terms temporal evolution, F1($\mathbf{x}$, $\mathbf{y}$, t) and F2($\mathbf{x}$, $\mathbf{y}$, t), from U, where:
  $\mathbf{x}$ is the observer location
  $\mathbf{y}$ is the probe location

3) Integrate F1 and F2 over S to obtain the sound pressure level (SPL):
  SPL($\mathbf{x}$, St) [dB]

4) Integrate SPL over St to obtain the overall SPL:
  OASPL($\mathbf{x}$) [dB]

Acoustic analysis comparison for iLES/ILSA on the high-order mesh





Summary

Channel test case

- iLES and ILSA have been compared in a WMLES turbulent channel.
- ILSA improves the turbulence statistics wrt. iLES in both DGSEM and FV discretizations.
- The ILSA eddy viscosity follows the flow structures even in highly anisotropic WRLES grids.

JEAN nozzle test case

- A highly anisotropic linear mesh and a quadratic mesh have been compared.
- Large mesh-related oscillations appear on the aerodynamic profiles of the linear mesh.
- While the quadratic mesh helps mitigating the oscillations, results are not improved.
- ILSA slightly improves the iLES results.

Future work

- Add tripping/turbulent inlet in the JEAN test case.
- CRM high-lift geometry with DGSEM/FV using WM and ILSA.

Progress in high-order large-eddy simulation of aeronautical flows using the integral-length scale approximation turbulence model

B. Font*, S. Pezzano, F. Naddei, M. Montagnac, O. Lehmkuhl

Thanks!

Download the presentation

@bernat_font

HiFiLeD Symposium 2022

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

ONERA
THE FRENCH AEROSPACE LAB

NextSim
Next generation of industrial aerodynamic simulation code

EuroHPC
Joint Undertaking