Recent DES results for aerodynamic and aeroacoustic applications in OpenFOAM

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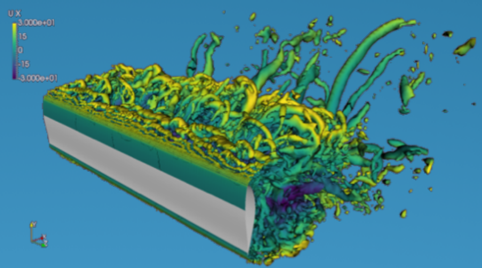

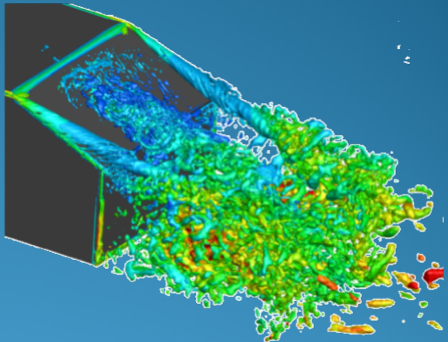

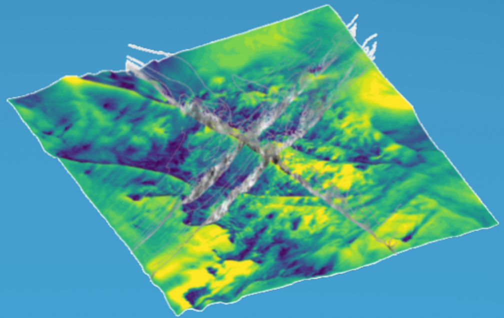

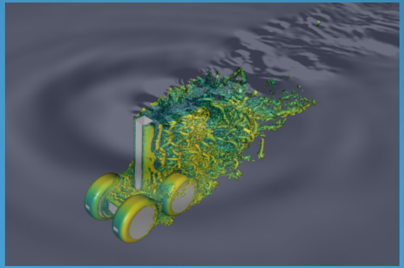

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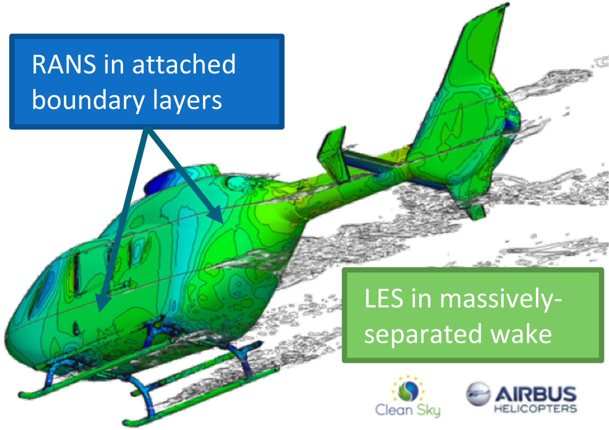
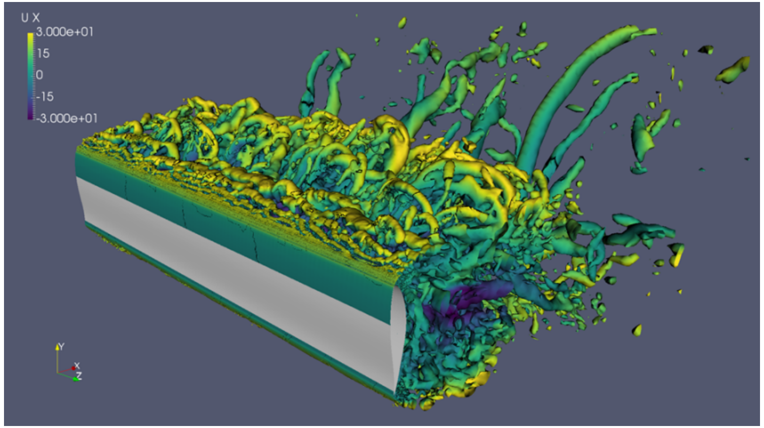
Introduction

- Detached-Eddy Simulation (DES) is a popular hybrid RANS-LES method for efficient, turbulence-resolving simulations at high Reynolds number
- Increasingly applied for practical applications, e.g.:
  - Flow prediction for cases where RANS is insufficiently accurate (e.g. highly-unsteady, massively-separated, three-dimensional flows)
  - Direct aeroacoustic simulation, where turbulent noise sources need to be resolved
- Continuing development of DES-based methods since their introduction by Spalart et al. (1997) has led to significant improvements
- A series of examples of DES application will be given in this talk:
  - "Natural" DES for wind turbine profile at $\alpha = 90°$
  - Grey-area improved formulation:
    - Delta wing
    - Ahmed body
  - Synthetic turbulence generator for DES of atmospheric boundary layer over complex terrain
  - Broadband noise prediction of Rudimentary Landing Gear on unstructured grids

Example of "natural" DES

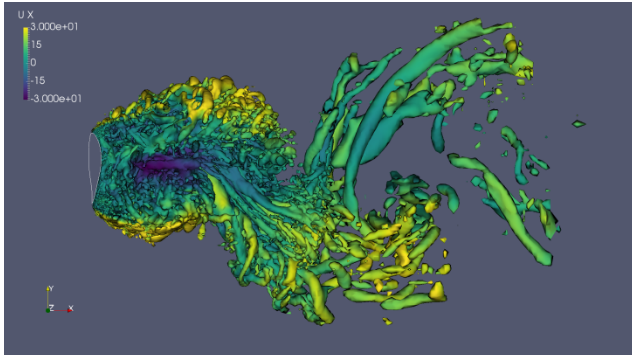


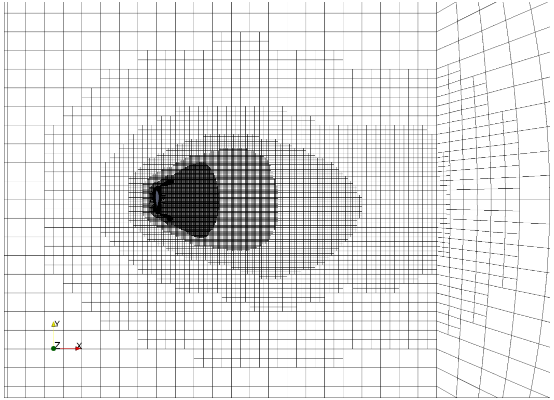
Natural DES of wind turbine blade at $\alpha = 90°$



Wind turbine blade at $\alpha = 90°$

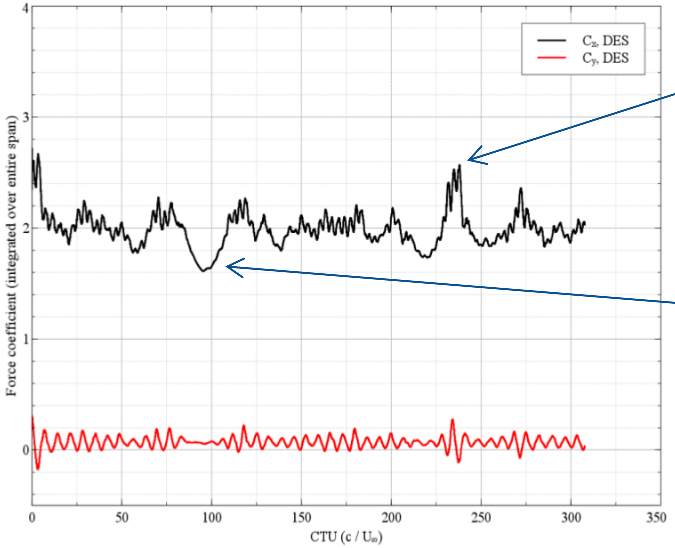
- Aerodynamic data needed in deep stall
- (U)RANS highly unreliable for massively-separated flows
- A “natural DES” application
- AVATAR NTUA18 profile at 90° angle of attack
  - Profile defined by National Technical University of Athens for AVATAR EU project
  - No measurement data available for high angles of attack
- Grid generated with *snappyHexMesh*
  - 11.61M cells
  - Spanwise domain size of 6 chord lengths
  - Refinement zones based on draft mesh DES
- Simulations with SA-DDES and SST-DDES
  - “Delayed DES” of Spalart et al., 2006 includes shield function designed to ensure RANS treatment of entire attached BL
- Hybrid convection scheme of Travin et al. (2000)
  - 2nd order CDS in regions of vortical flow
  - 2nd order upwind in irrotational flow regions
- Flow field statistics conducted over 275 CTU following initial transient of 35 CTU

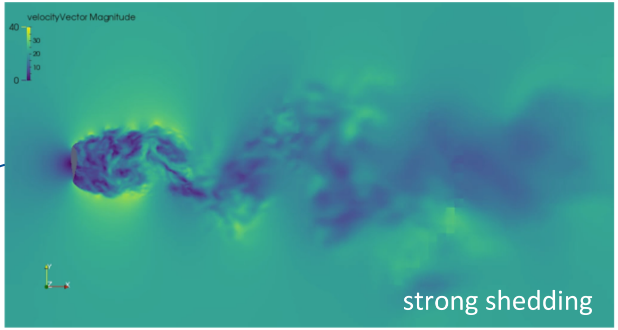


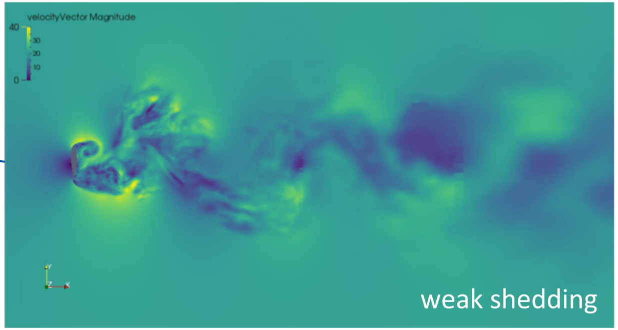


Unsteady flow behaviour

- Highly unsteady bimodal flow:
  - Modulates randomly between strong and weak shedding regimes
  - Very large statistical sample required

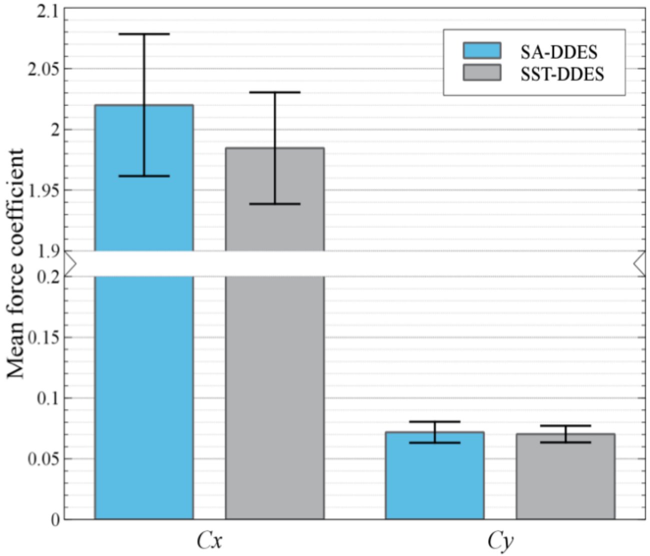






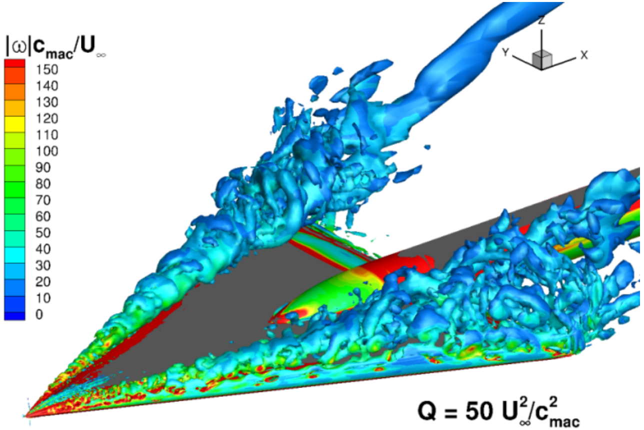
Mean lift and drag coefficients

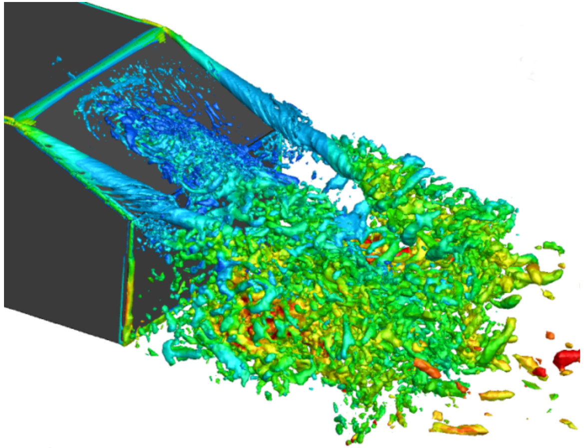
- Error bars depict 95% confidence interval (CI) due to statistical uncertainty (computed with in-house *Meancalc* tool)
- No statistically significant difference between SA-DDES and SST-DDES



Component	Model	Mean	95% CI
C_x	SA-DDES	2.02	±0.058 (±3%)
	SST-DDES	1.99	±0.046 (±2%)
C_y	SA-DDES	0.0718	±0.0086 (±12%)
	SST-DDES	0.0703	±0.0068 (±10%)

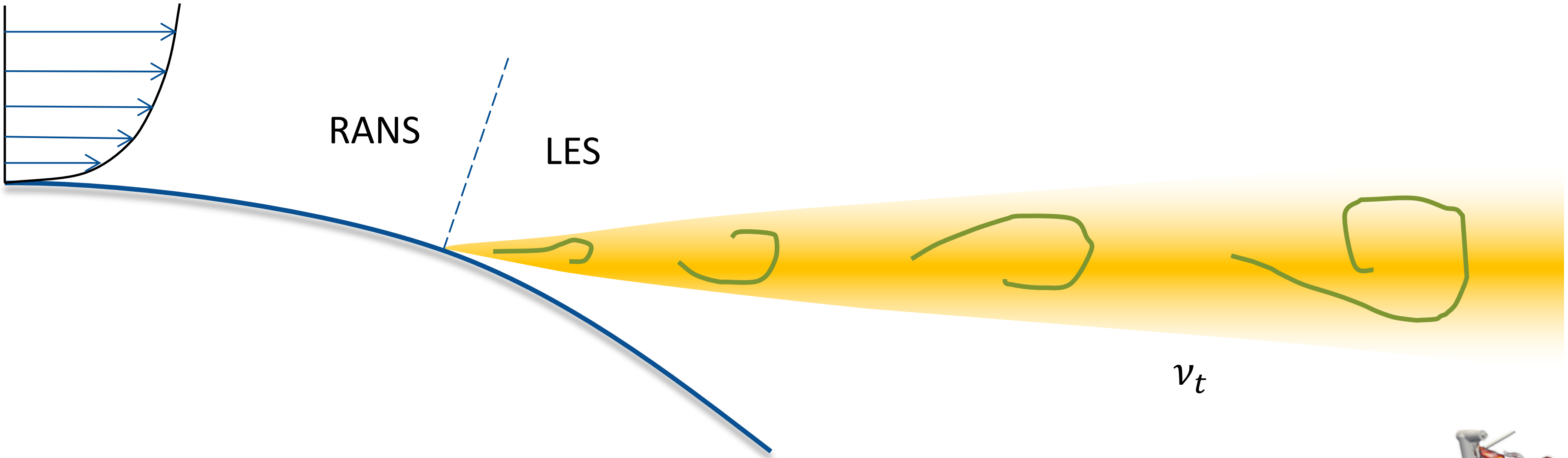
Grey-area improved formulation





The Grey Area problem

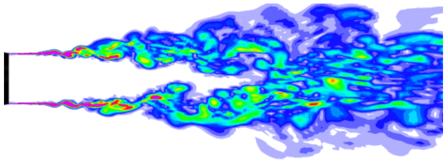
- RANS to LES transition region in the early shear layer
- Model switches to LES mode after separation
  - No turbulent fluctuations from upstream
  - Fluctuations must be generated by natural shear layer instability



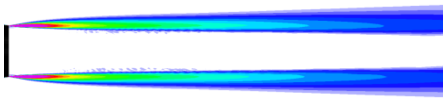
Impact of the Grey Area in practice

- Unfortunately, weakly-separated flows generally represent the most important cases in practice
  - Limits of performance
  - Flight envelope boundaries
  - Maximum turbine blade loading
- Both RANS and current hybrid RANS-LES methods are unreliable here
- Another prominent example of the Grey Area problem in practice:
  - Jet noise prediction

What we want…

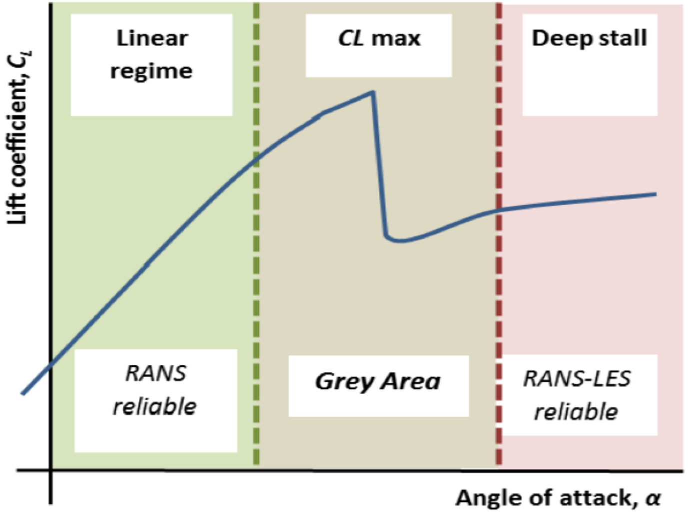


…what we get!



Schematic as example for wing flows

Lift coefficient vs. angle of attack



Improved DES with accelerated RANS to LES transition

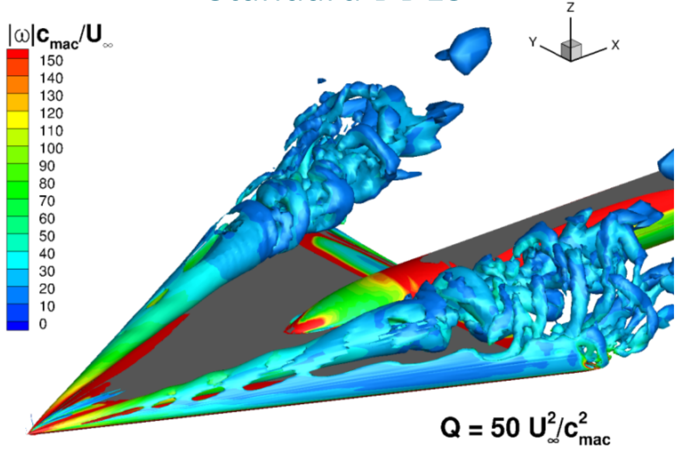
- Approach presented at 5th Symposium on Hybrid RANS-LES Methods:

  C. Mockett, M. Fuchs, A. Garbaruk, M. Shur, P. Spalart, M. Strelets, F. Thiele, A. Travin: Two non-zonal approaches to accelerate RANS to LES transition of free shear layers in DES. In: Progress in Hybrid RANS-LES Modelling, Springer (2015)
- Our approaches aim to improve Grey Area by reducing eddy viscosity in the early shear layer
- Development priorities:
  - DES performance should not be degraded in other respects
  - Retain non-zonal nature of approach
  - Robust and applicable to complex cases
  - Generally-applicable method
- Two key ingredients:
  - A vorticity-adapted definition of the grid filter, denoted $\tilde{\Delta}_{\omega}$
  - Adopts form of σ model (Nicoud et al.) in LES-mode region

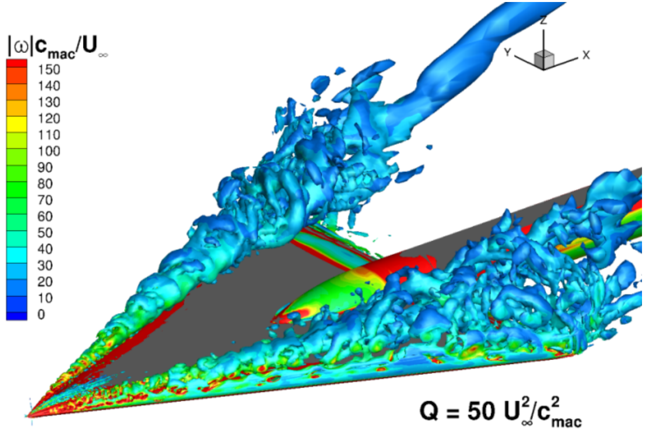
Delta wing

- Sharp leading edge, $Re_{mac} = 10^6$, M = 0.07, $\alpha = 23°$
- Experimental data of Furman & Breitsamter, Aerospace Science & Technology, 24-1, 32-44, 2013
- Models compared on the same grid (6.3M cells, kindly provided by J. Kok, NLR)
- Snapshots of Q criterion

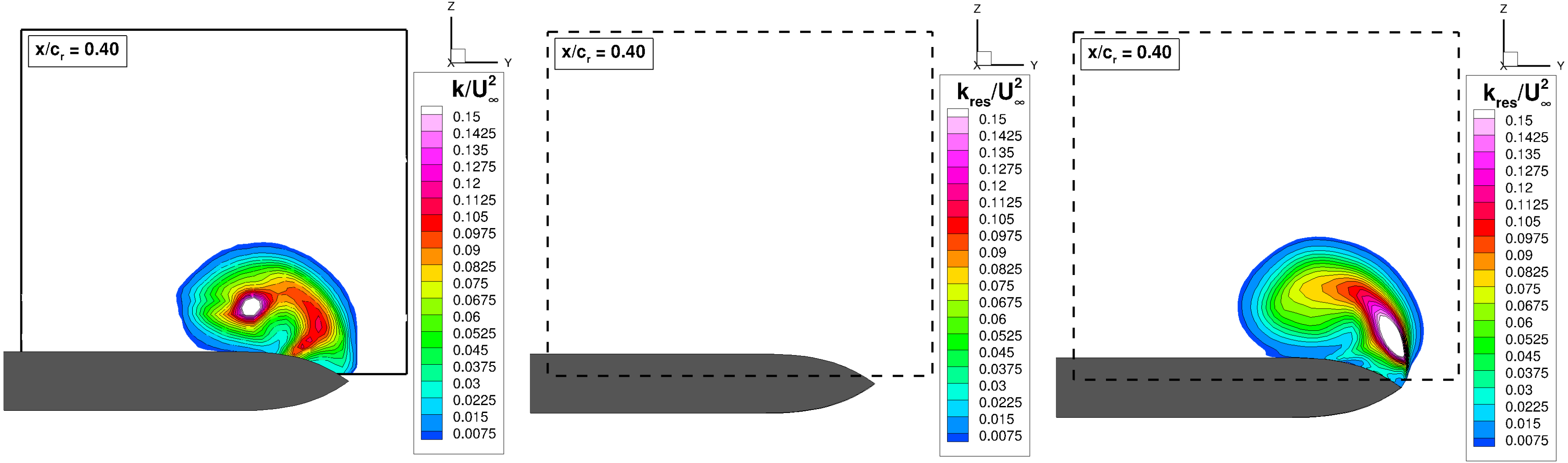
Standard DDES



Improved DDES



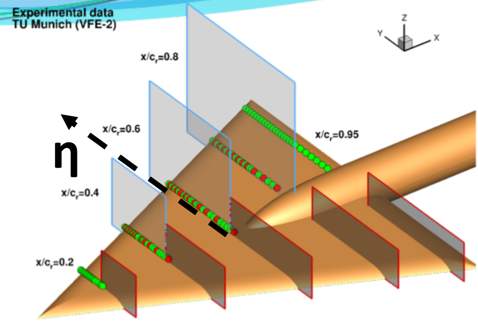
Resolved TKE at $x/c_r = 0.4$



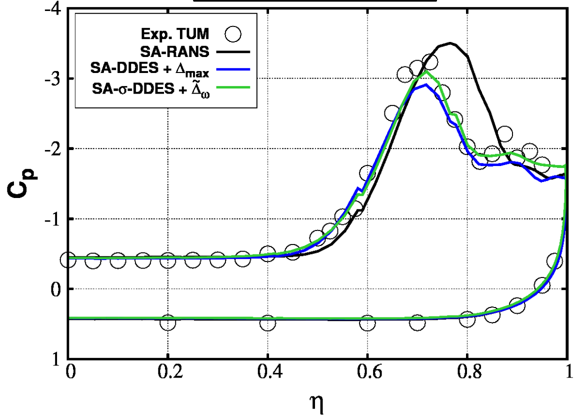
Exp. HWA | **SA-DDES + Δ_{max}** | **SA-σ-DDES + $\widetilde{\Delta}_{\omega}$**

Mean surface pressure

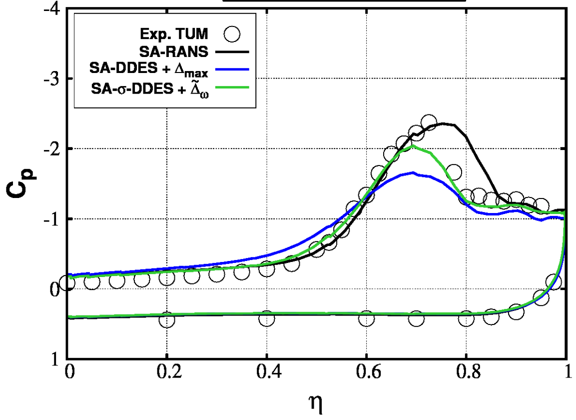
Exp. TUM ○
SA-RANS
SA-DDES + Δ_{max}
SA-σ-DDES + $\tilde{\Delta}_\omega$



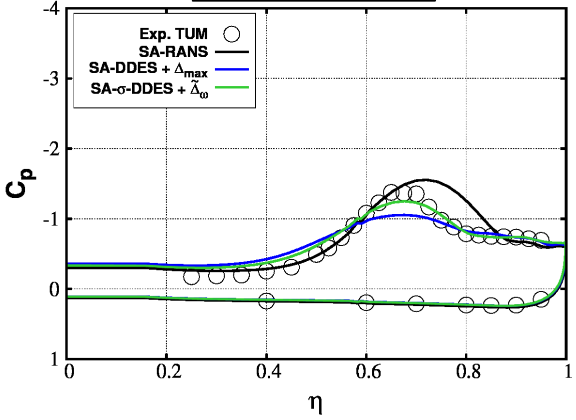
$x/c_r = 0.40$



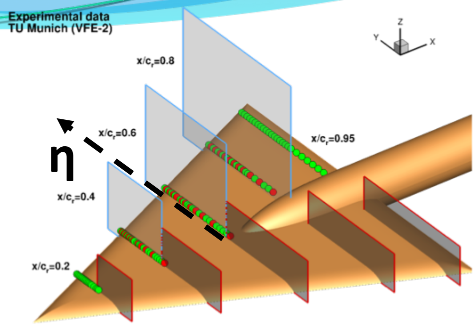
$x/c_r = 0.60$



$x/c_r = 0.80$

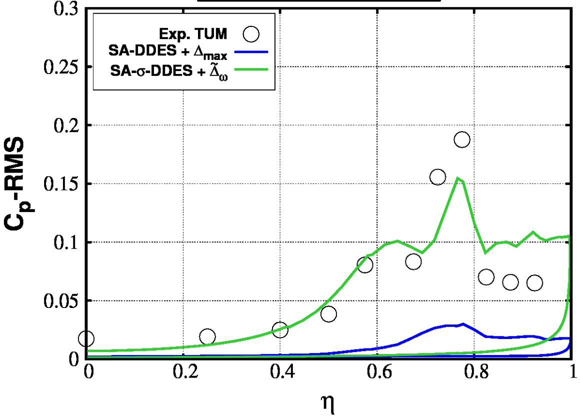


Surface pressure fluctuations

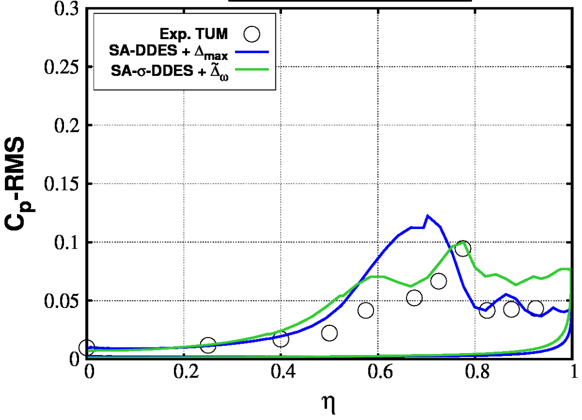


Exp. TUM	○
SA-RANS	black line
SA-DDES + Δ_{max}	blue line
SA-σ-DDES + $\tilde{\Delta}_{\omega}$	green line

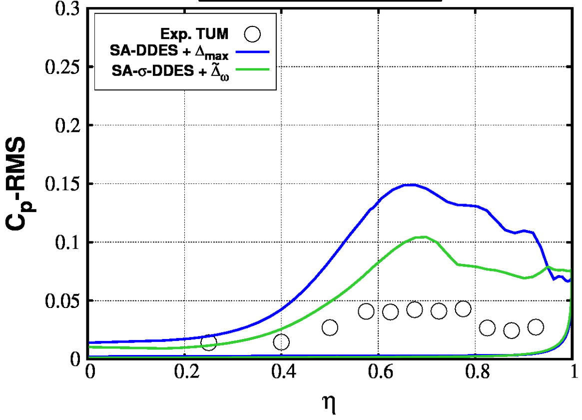
$x/c_r = 0.40$



$x/c_r = 0.60$

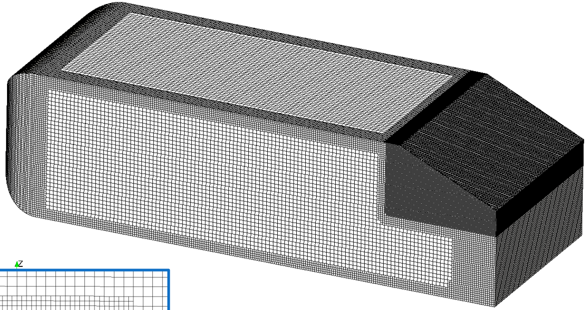


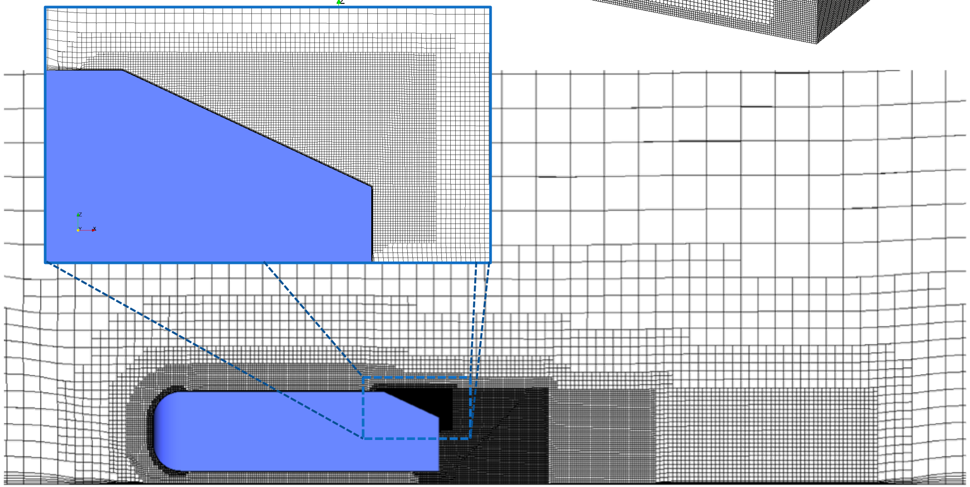
$x/c_r = 0.80$



Ahmed body (25° slant angle)

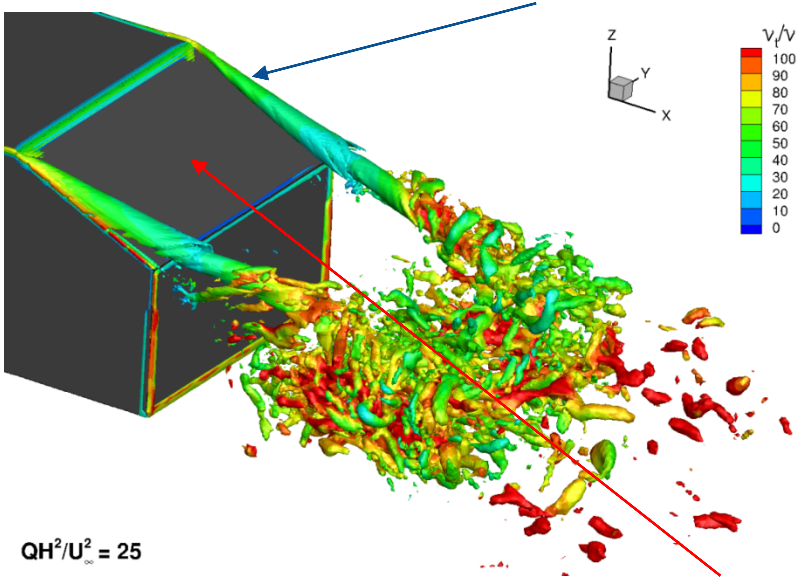
- Initial results comparing grey-area improved DDES with standard DDES
- Prediction of correct flow topology for 25° case a well-established challenge for RANS and DES
  - Separating-reattaching flow over slant interacts with edge vortices
  - Vortices and shear layers strongly affected by grey-area problem
- Relatively coarse grid generated with snappyHexMesh
  - 5 prism layers, y^+ around 30-50
  - 4.6M cells
- Physical parameters:
  - Free-stream velocity: $U_\infty = 40\ m/s$
  - Wind tunnel model: $H = 0.288\ m$, $L = 1.044\ m$
  - Reynolds number: $Re_H = 7.68 \times 10^5$





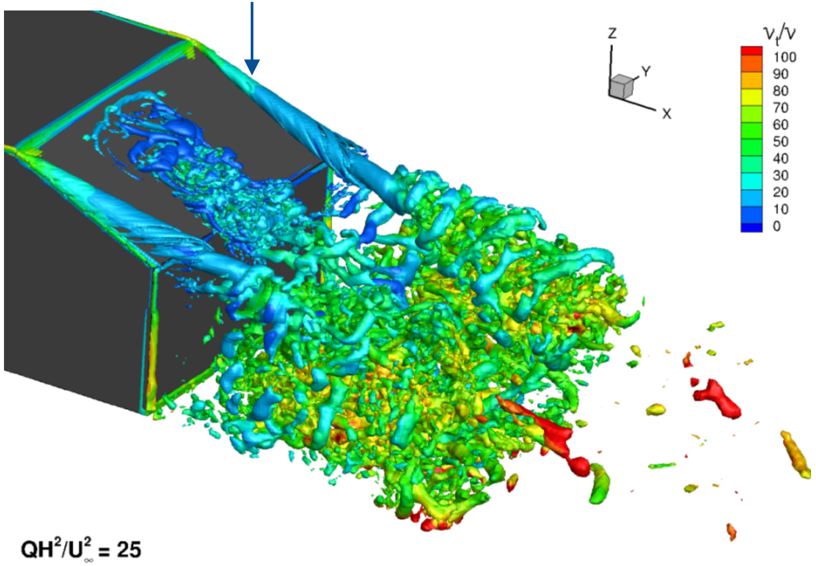
Instantaneous flow

significantly higher eddy viscosity in corner vortices for std. DDES



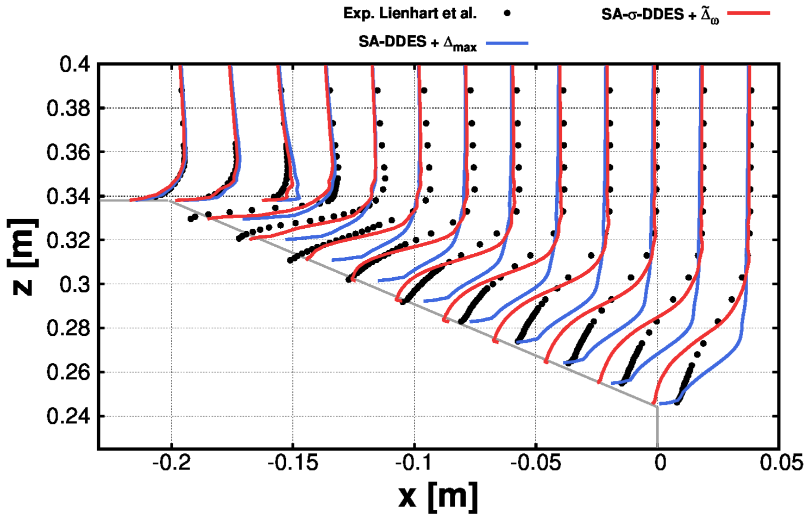
no resolved turbulence on slant

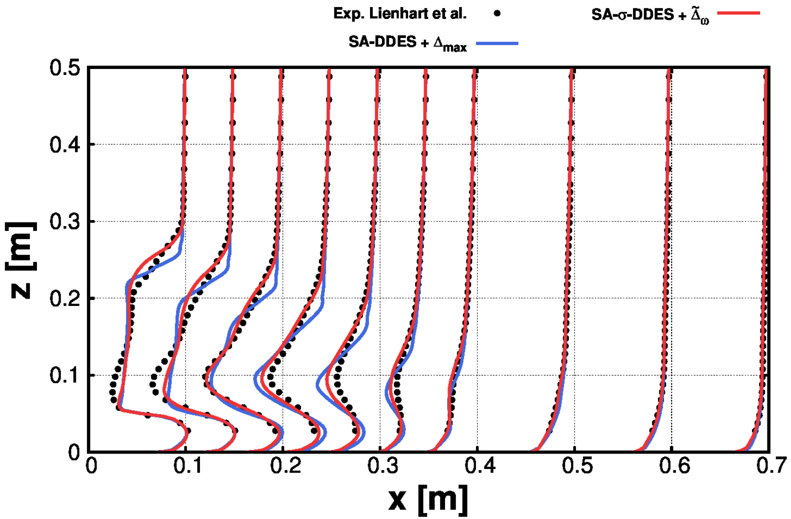
Std. DDES



Grey-area improved DDES

Mean streamwise velocity on symmetry plane





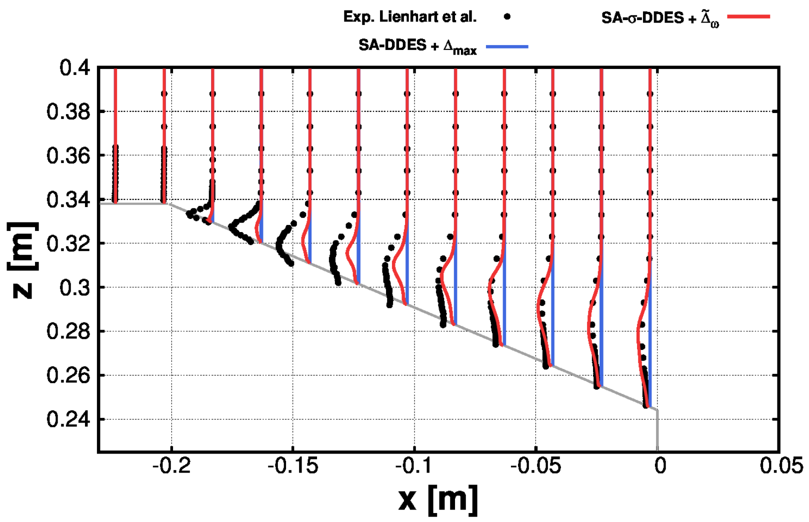
on slant

downstream of rear

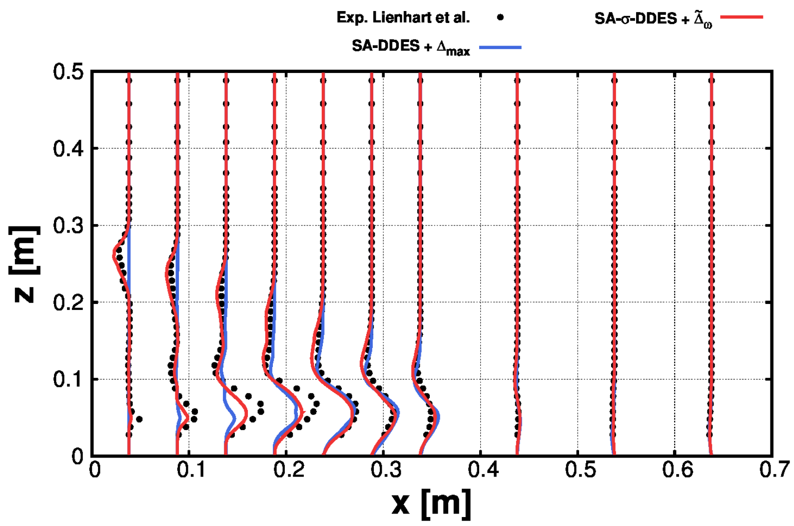
Significant improvement of results through grey-area reduction, but not yet perfect.

→ Increased grid resolution?

Resolved Reynolds shear stress $\overline{u'w'}$ on symmetry plane



on slant

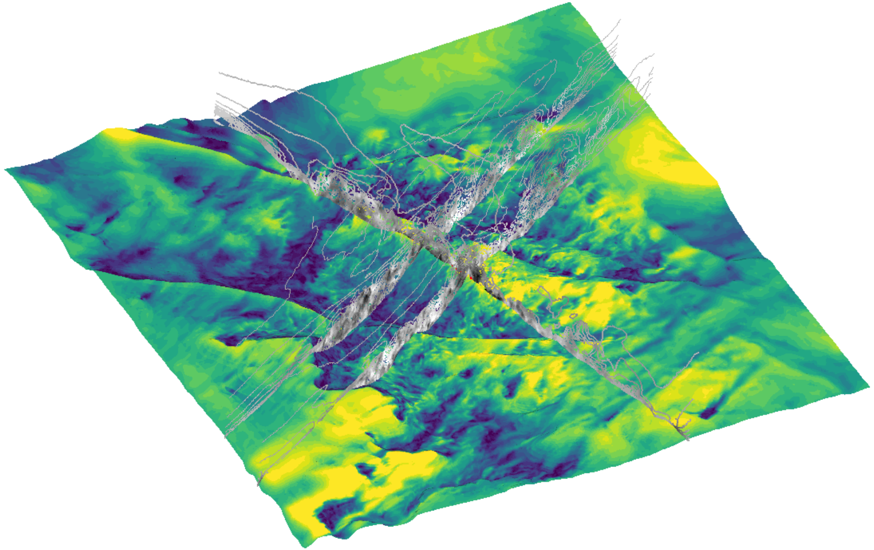


downstream of rear

Significant improvement of results through grey-area reduction, but not yet perfect.

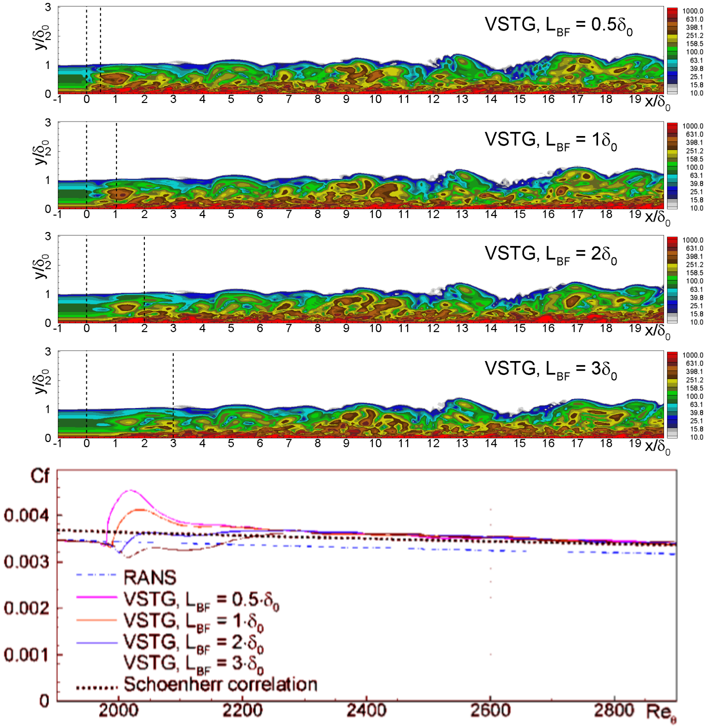
→ Increased grid resolution?

Atmospheric boundary layer over complex terrain



Volumetric Synthetic Turbulence Generator (VSTG)

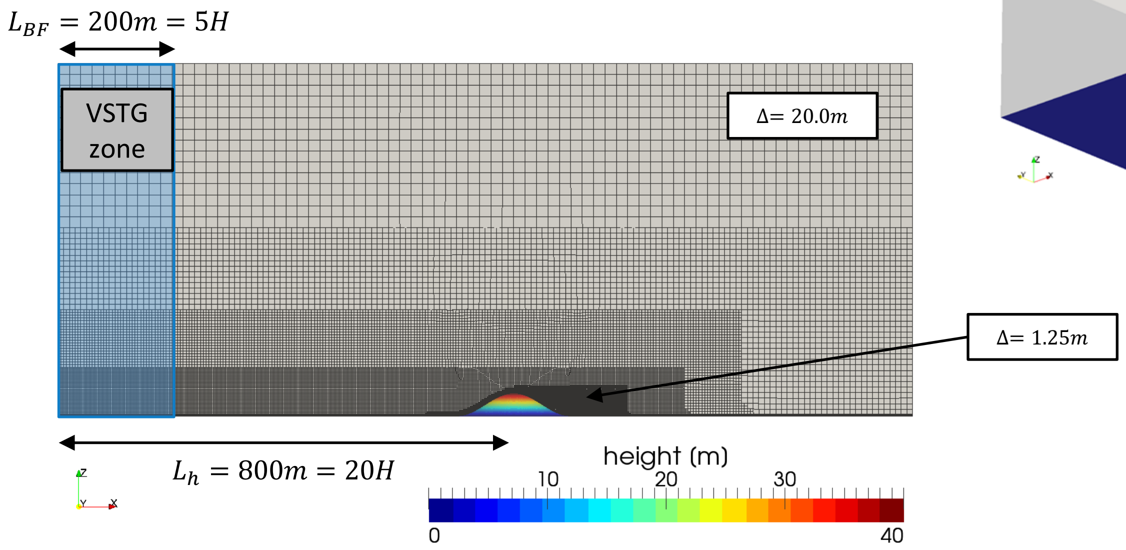
- DES operating as **wall-modelled LES** (resolved turbulence inside BL, RANS confined to thin near-wall layer) using **IDDES** variant of Shur et al. (2008)
- Resolved atmospheric turbulence must be represented at inlet to scale-resolving domain
- VSTG (**V**olumetric **S**ynthetic **T**urbulence **G**enerator) method of Shur et al. (2017) implemented in OpenFOAM:
  - Generates resolved turbulence from precursor RANS of ABL
  - Reduces LES computational domain whilst taking mean flow effects of upstream domain into account
  - Volume source terms in momentum and turbulence equations
  - More easily applicable to complex geometries than most 2D synthetic turbulence methods
  - Source terms active in user-defined zone
  - Reasonable computational overhead

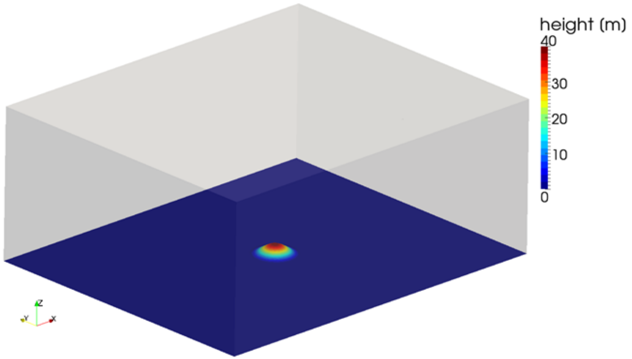


Results from Shur et al., 2017

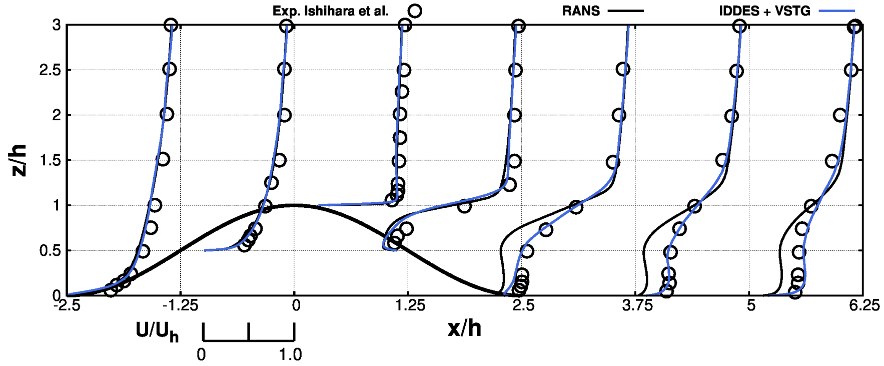
Validation of VSTG implementation: 3D hill test case

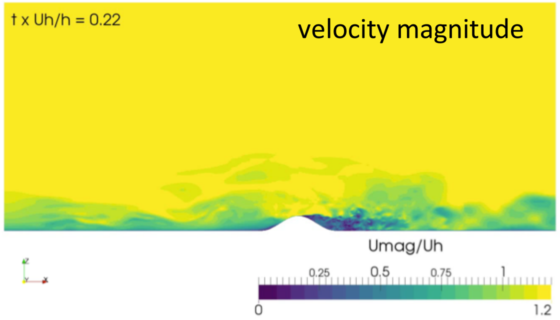
- Smooth 3D hill (analytical shape):
  - Experimental measurements conducted by Ishihara et al. (1999)
  - Complex flow pattern, difficult to capture with RANS → SST-IDDES used
  - Resolved incoming turbulence key for good prediction

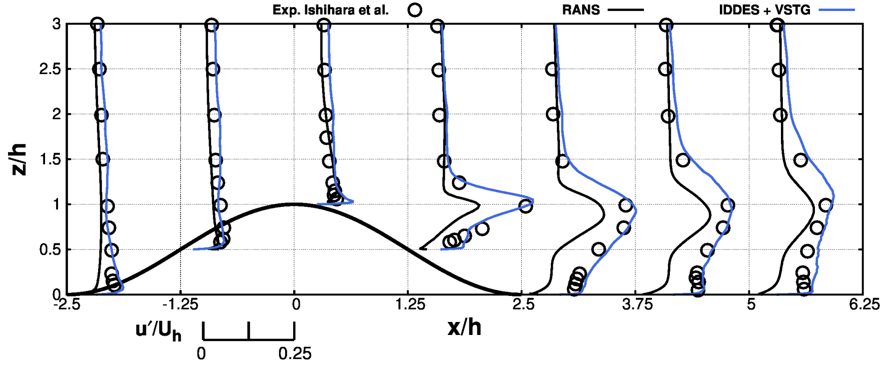


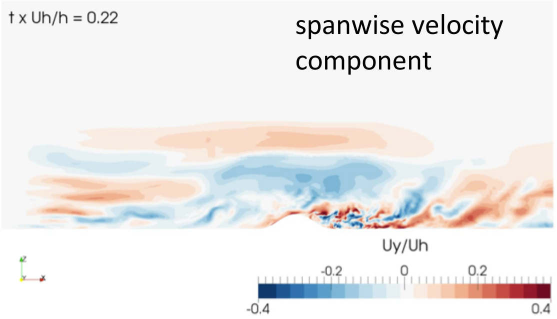


Validation of VSTG implementation: 3D hill test case



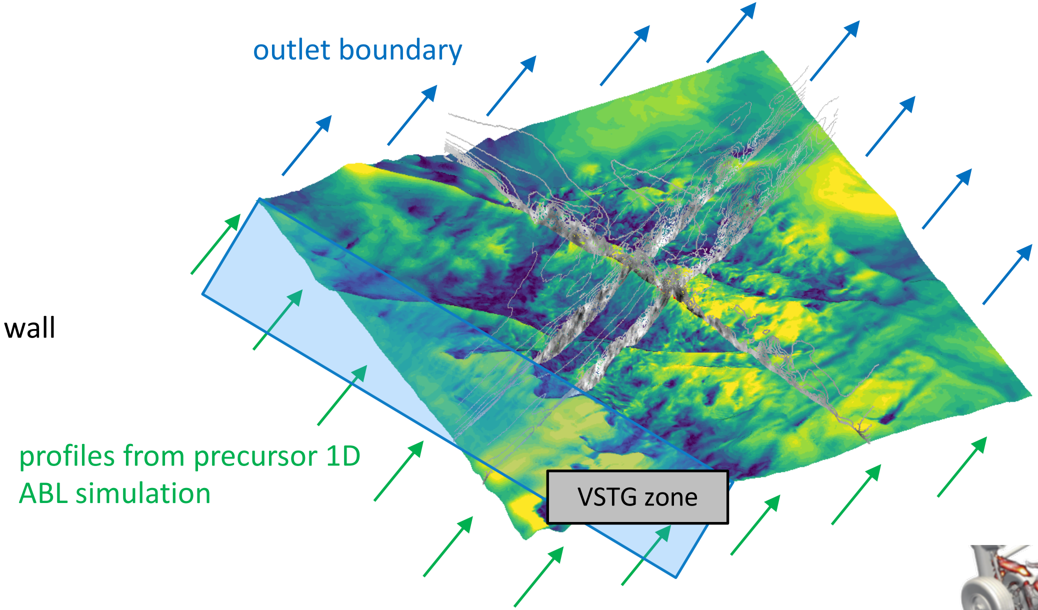






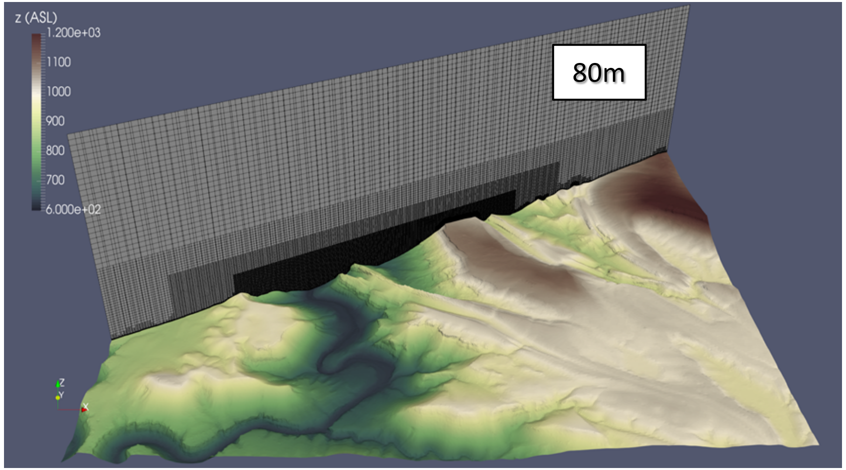
Complex terrain simulation

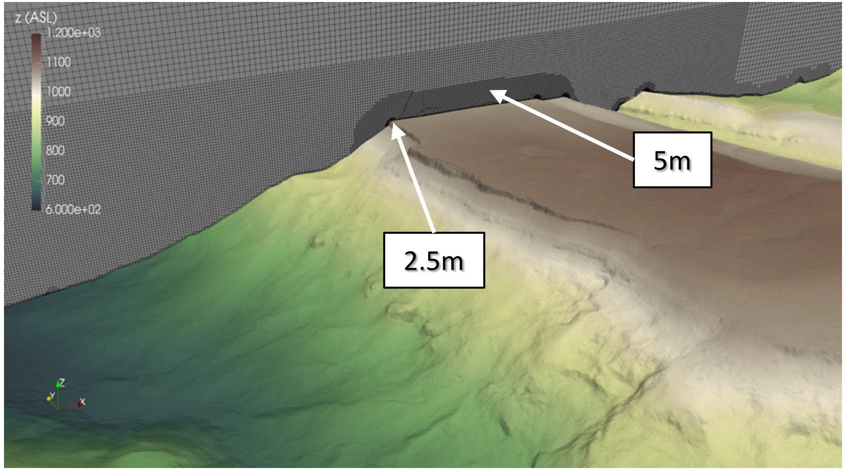
- Functionality test of VSTG for challenging real-world application
- Wind turbine site in northern Spain:
  - Terrain with large elevation differences
  - 15 wind turbines & 2 measurement masts
- CFD setup:
  - Area of 10km x 10km is simulated
  - Turbulence model: SST-IDDES
  - VSTG applied
  - Transient SIMPLE-based solver
  - Incorporation of Coriolis force and uniform wall roughness
  - Neutral stratification
  - Geostrophic wind: $|U|_g = 15\,m/s$



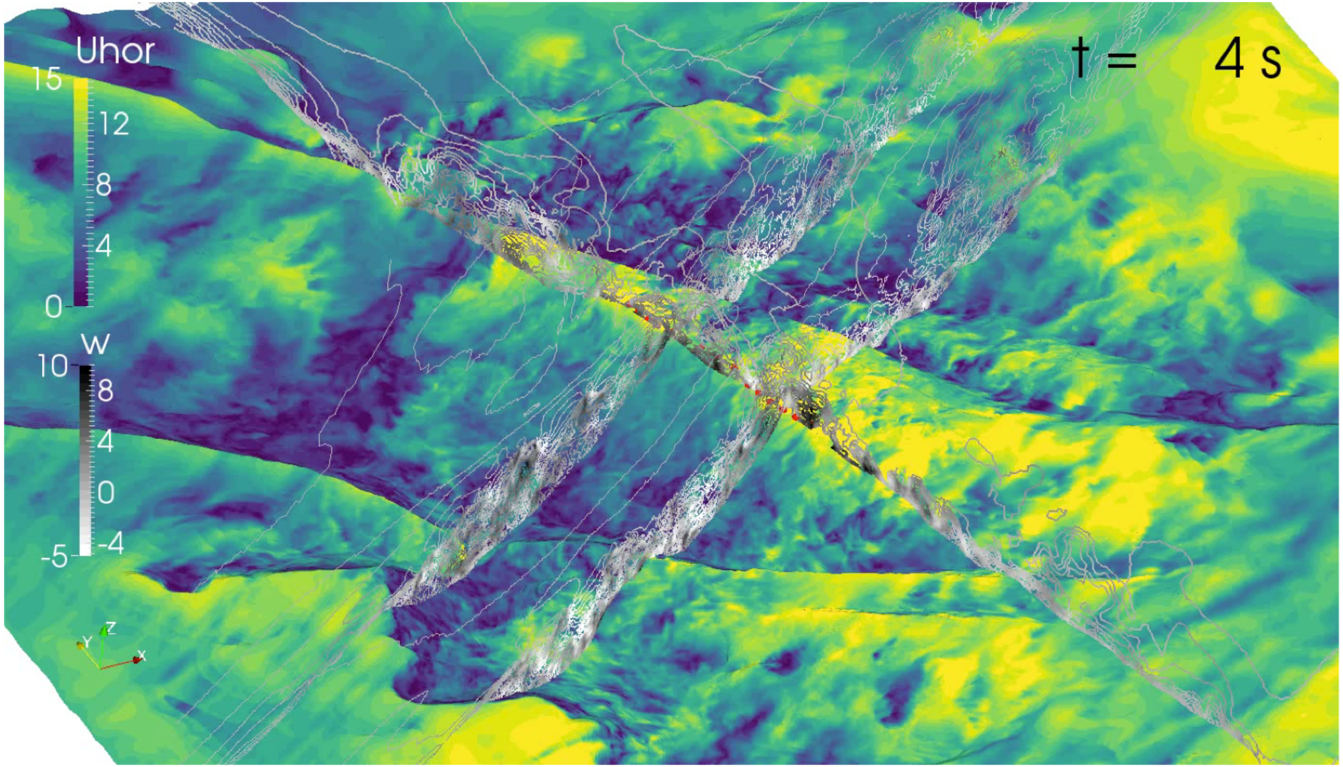
Complex terrain simulation

- Mesh generation with snappyHexMesh
  - 20M cells
  - Variable resolution between 80m – 2.5m



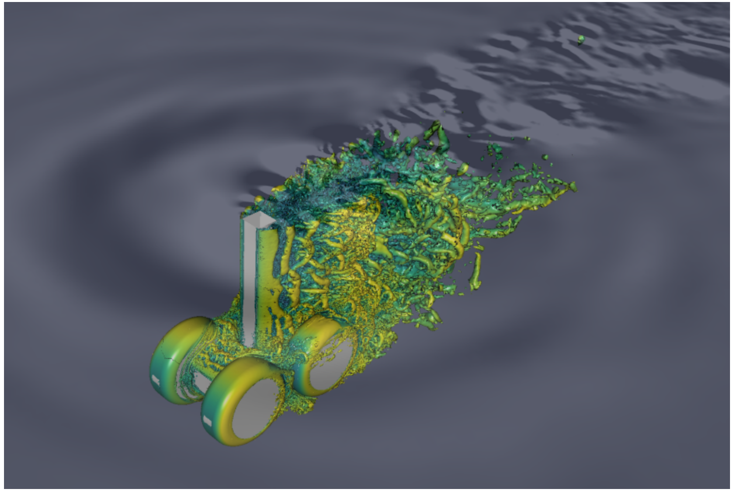


Complex terrain simulation



(validation with measurement data pending)

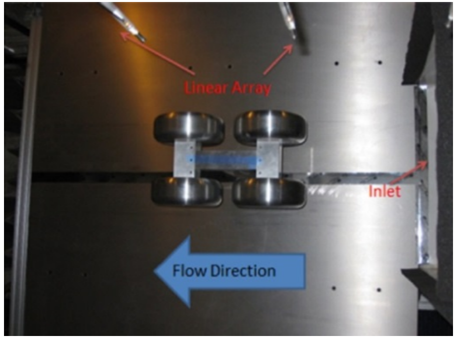
Broadband noise prediction on unstructured grids



Simulation approach and test case

- Requirements for direct aeroacoustic simulation:
  - Accurate, scale-resolving simulation methodology (grey-area improved DES)
  - Compressible solver with low spurious noise
  - Far-field integration method (Ffowcs Williams & Hawkings approach)
    - Solid data surfaces applicable at low Mach numbers (dipole sources only)
    - Permeable data surfaces encompassing source region needed for higher Mach numbers (additional quadrupole sources)
- Rudimentary Landing Gear (RLG) case:
  - Aerodynamic and aeroacoustic measurements available
  - From AIAA BANC workshop series
  - Generic 4-wheel landing gear mounted on flat “ceiling” plate
  - $Re_D = 1.0{\times}10^6, M = 0.12$

Aerodynamic measurements at National Aerospace Laboratories, Bangalore / India

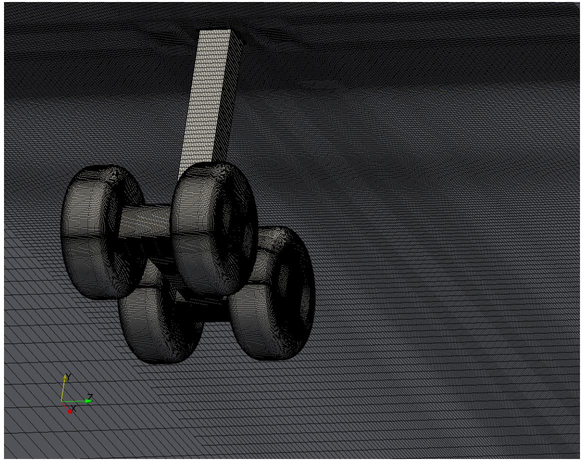


Aeroacoustics measurements at University of Florida / USA

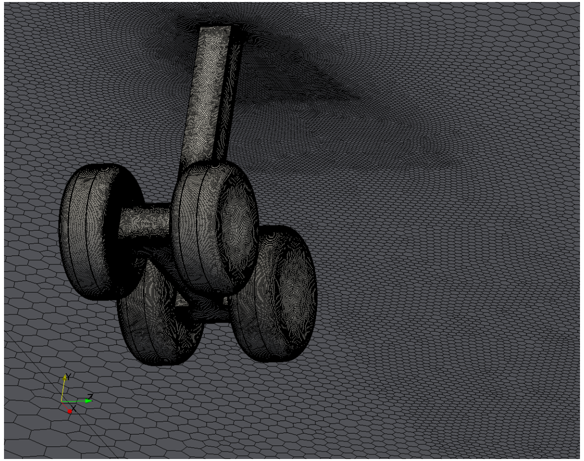
Grids

- Structured (ICEM-CFD), polyhedral-unstructured (ANSA) and hexahedral-unstructured (snappyHexMesh) grids compared
- All designed to resolve acoustics up to $St \approx 10$, prism layers down to $y^{+} \approx 1$

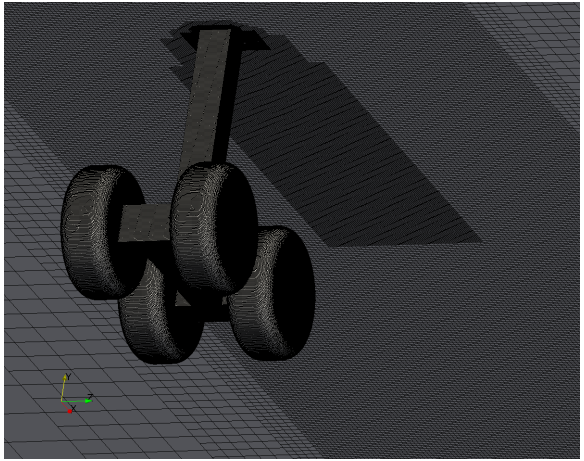
structured, 37M cells



polyhedral, 18M cells



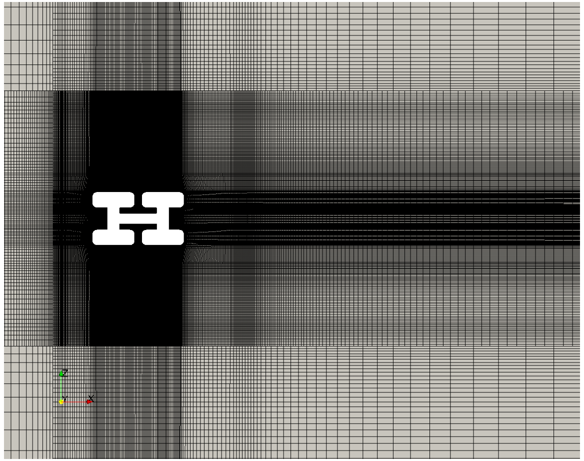
SHM, 21M cells



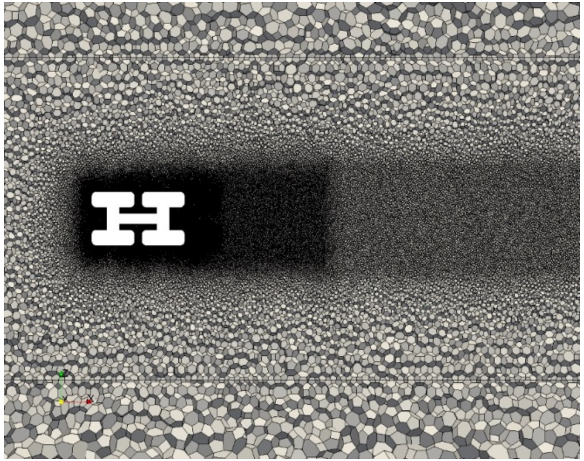
Grids

- Structured (ICEM-CFD), polyhedral-unstructured (ANSA) and hexahedral-unstructured (snappyHexMesh) grids compared
- All designed to resolve acoustics up to $St \approx 10$, prism layers down to $y^+ \approx 1$

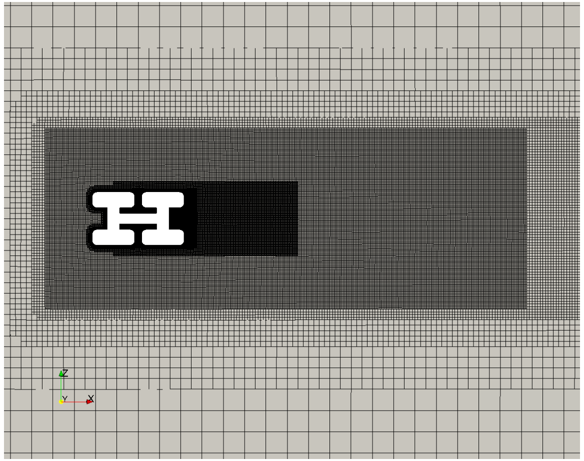
structured, 37M cells



polyhedral, 18M cells



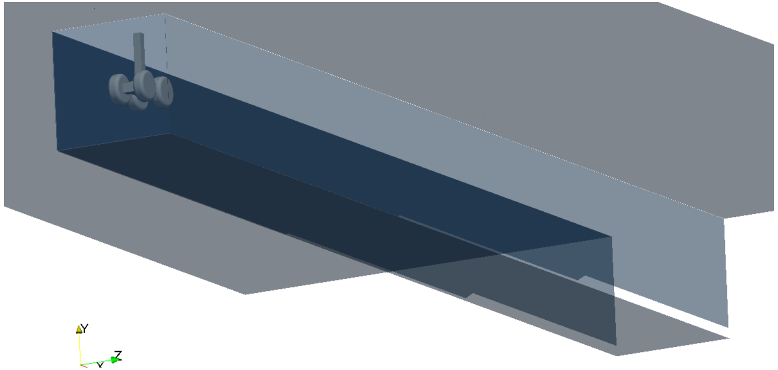
SHM, 21M cells



FWH data surfaces

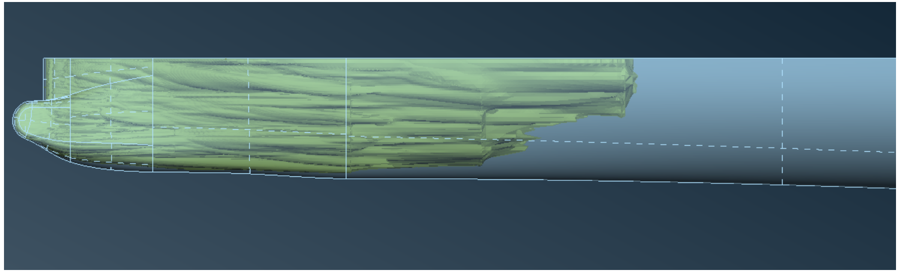
- Alternative porous FWH data surfaces tested

Std. FWH surfaces



- Simple surface definition to safely avoid hydrodynamic fluctuations, which would induce spurious noise
- Evaluated on all grids

Tailored FWH surfaces

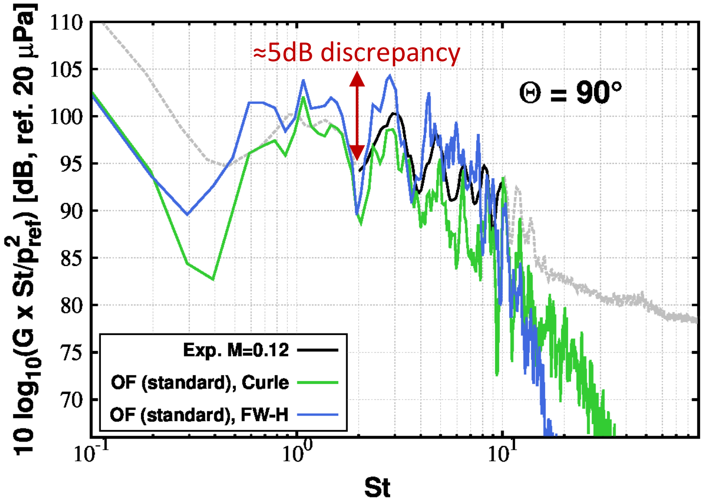


- Iso-surface of sensor function evaluated in precursor simulation
- Intended to define optimal FWH placement: As close to source region as possible, to minimise attenuation of high frequencies
- Scope for automated process
- Evaluated on SHM grid only

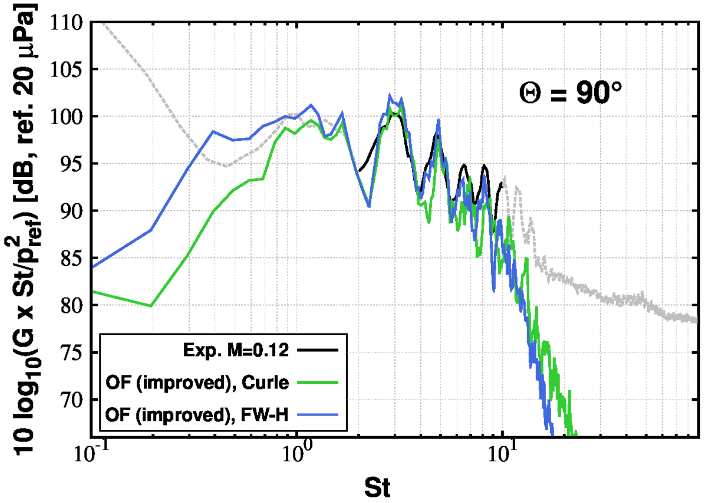
Improved solver with low spurious noise

- At the low Mach number of the RLG case (M=0.12), quadrupole noise should be negligible meaning that solid and permeable FWH approaches should agree
  - Used as indicator for spurious, numerical noise

Std. solver



Improved solver



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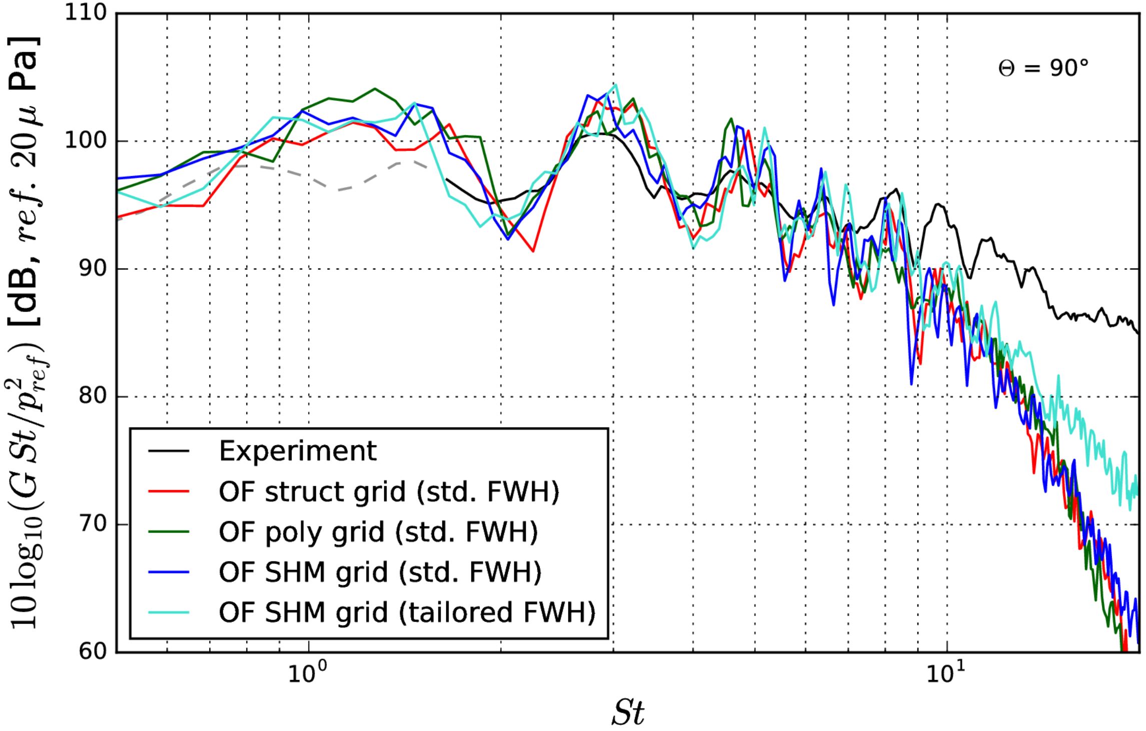
Comparison of grids and FWH data surfaces



All grid types deliver very comparable results

Agreement with measurements within ≈2dB up to grid resolution limit of *St* ≈ 10

Tailored FWH surface increases resolution of high frequencies

Conclusions

Conclusions

- Growing number of examples showing benefits of DES for high-fidelity aerodynamic and aeroacoustic simulation in OpenFOAM
- Very wide range of applications demonstrate flexibility of method (and, of course, OpenFOAM)
- Our implementation of DES features integrated in openfoam.com version since v3.0+:
  - Standardised, validated & calibrated implementations of DES97, DDES and IDDES based on S-A and SST models
  - Hybrid convection scheme
    - Give it a try – feedback welcome!
- New grey-area improved formulation improves prediction for cases with weaker shear layer instability without damaging performance for “natural DES” flows
- Accurate prediction of challenging low-Mach number aeroacoustics for different unstructured grid types
- Sensor function for optimal FWH surface placement:
  - Improves high-frequency resolution
  - Reduces scope for user error
  - Potential for automated procedure

7th Symposium on Hybrid RANS-LES Methods

7th HRLM

- Berlin, 17th-19th September 2018
- Local organiser: CFD Software E+F GmbH
- Abstract submission deadline: 30th April 2018
- Proceedings in Springer NNFM series
- Registration opening soon: Early bird deadline 23rd June 2018
  - https://hrlm7.sciencesconf.org

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Thank you for your attention

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