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Recent experiences of modeled-stress depletion using DDES & IDDES for the 30P30N three-element airfoil

Dr. Neil Ashton
Oxford e-Research Centre

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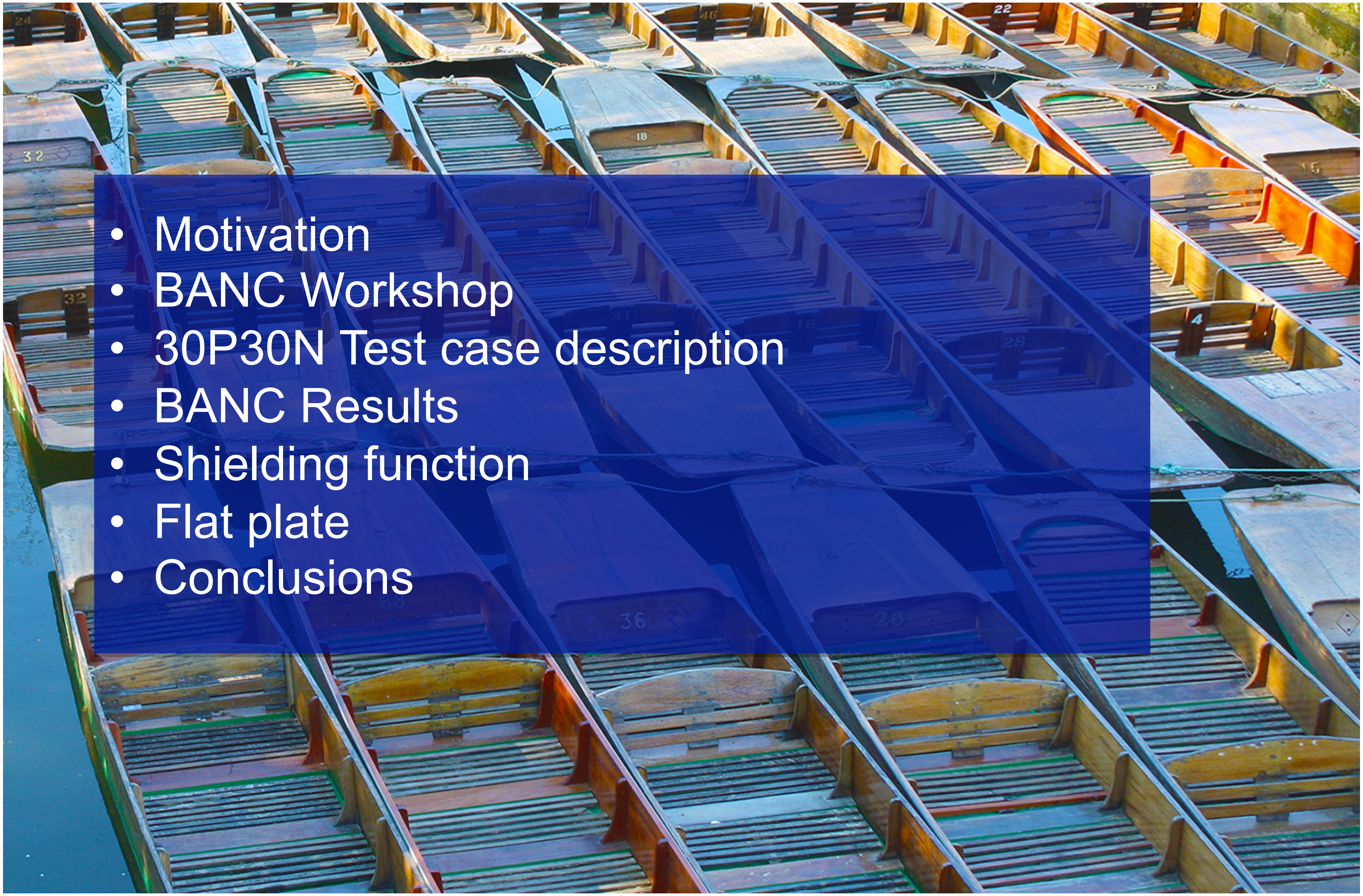


- Motivation
- BANC Workshop
- 30P30N Test case description
- BANC Results
- Shielding function
- Flat plate
- Conclusions

Dr Neil Ashton – University of Oxford

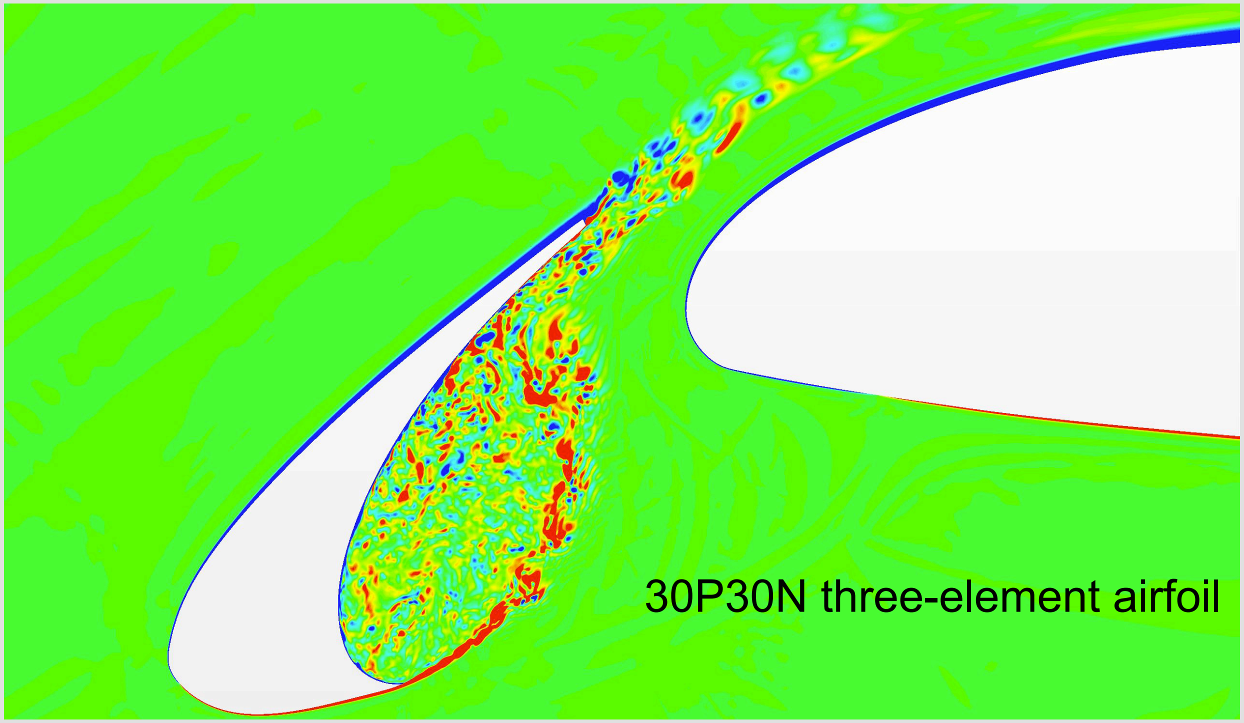
- Academic – PhD (University of Manchester) - Member of several automotive/aerospace EU projects (Airbus, DLR, VW, Rolls-Royce..)
- Engineer – CFD Engineer at Lotus F1 team (now Renault)
- Consulting for a range of companies e.g Audi, F1 Teams, Cervelo, British Cycling
- Chartered Engineer through IMechE

Motivation

- We're moving towards a fully digital design process
- Barriers are
  - Accuracy – **Turbulence Modeling (I'm biased!), Mesh, Numerics**
  - Turn-around time – **Time from CAD-PNG/PDF**
  - Hardware – **Regular access to > 10,000 cores**
  - Software – **Scalability, sustainability**

BANC Workshop

- AIAA workshop focused on assessing and improving methods for the accurate prediction of noise sources from an aircraft.
- Noise emissions crucial limiting factor in the expansion of current airports, both in terms of their operating hours and geographical location.
- A reduction in noise emissions could allow for longer operating periods and a decrease in the number and severity of planning delays



- A major contribution of noise radiation from a commercial airliner is its high-lift system, in particular the leading edge slat.
- The unsteady flow separation from the leading edge of the slat produces a separated shear layer which when reattaching further downstream produces a broadband noise source.

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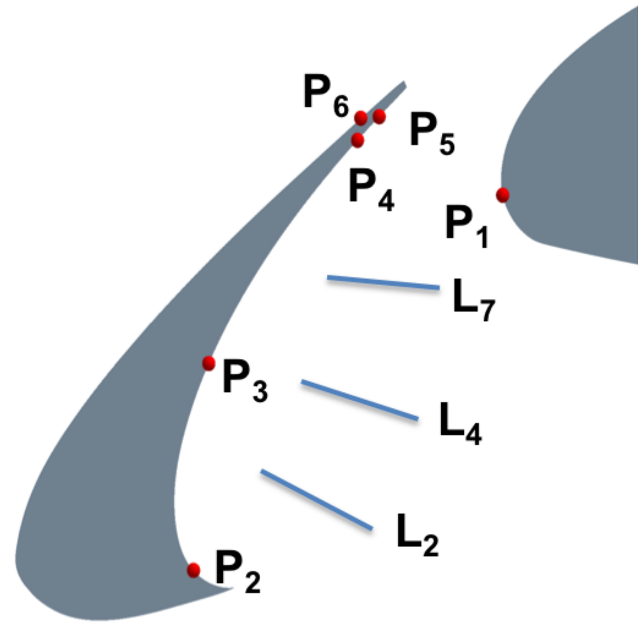
30P30N three-element airfoil



Several experimental results:

- Cl,Cd, Cp
- PIV planes for velocity components, Turbulent Kinetic Energy (TKE) and vorticity.
- Additionally surface pressure spectra around the slat cove region is available at several locations.

AoA	M	c (m)	Re	T
5.5 deg	0.17	0.457	1.7x10 6	295k

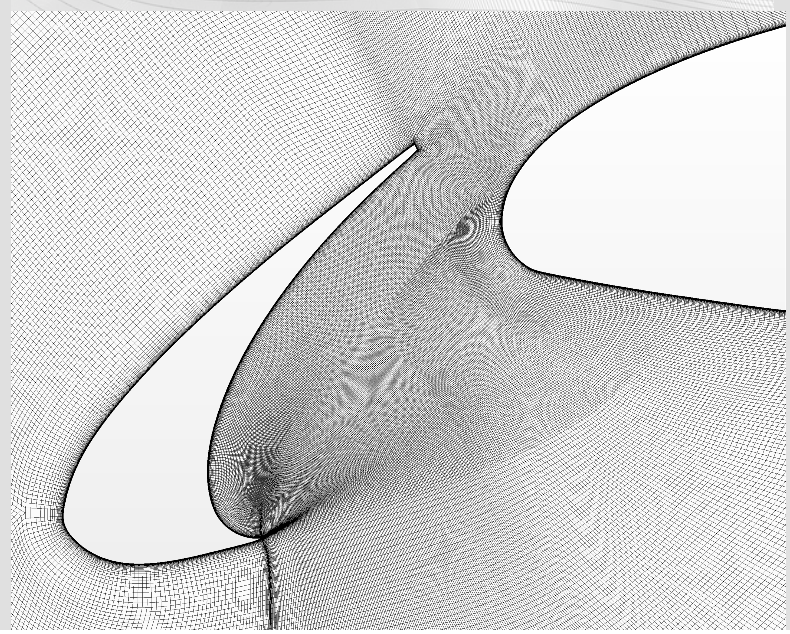
Turbulence Modelling

- Reynolds-Averaged Navier-Stokes (RANS) approaches are not suitable throughout the whole envelope
- Wall-resolved Large Eddy Simulation (LES) is prohibitively expensive for such a wall-bounded flow at this reasonable Reynolds number (even if the slat shear layer itself could be resolved).
- For this reason hybrid RANS-LES methods, which seek to combine the advantages of both RANS and LES methods are an attractive modelling choice. We focus on Detached-Eddy Simulation.

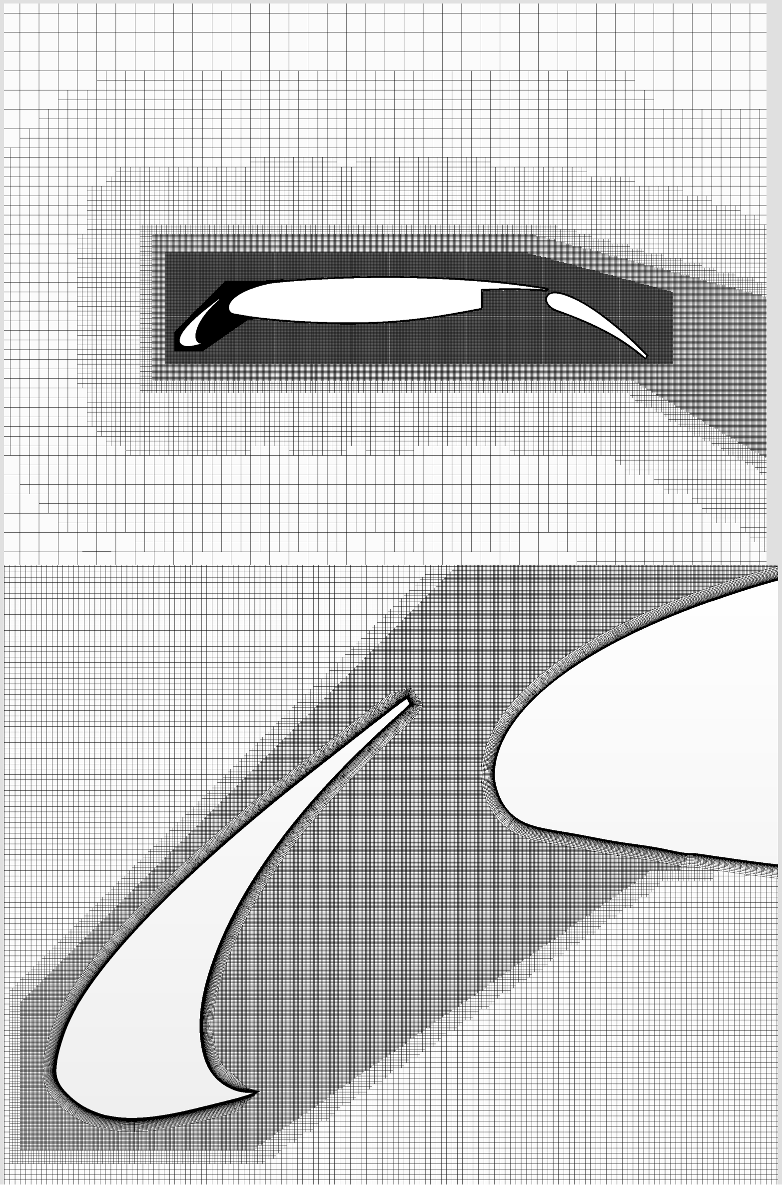
Meshing

- Whilst overset or structured meshes produce high-quality grids, these are not suitable for complex geometries whose design are changing frequently (enough that a meshing script cannot be adjusted).
- Unstructured meshes offer the ability to more easily adapt to new changes with minimum human input.
- The initial meshing setup phase can be time-consuming but then new CAD can be swapped in and out in an fully automated fashion.
- How do unstructured grids compare to structured? (common question!)

- 1-to-1 point matched multi-block structured grid kindly provided by JAXA
- 2D plane: 105 blocks, 271,739 points
- Y+ < 1
- Length in the spanwise direction is 2 inches (271 points)
- Total cell count: 73 million



- Unstructured grid consisting of body-fitted prismatic layers (1.1 stretching ratio) + hexahedral cells
- Isotropic refinement in the slat region
- Y+ < 1
- Length in the spanwise direction is 2 inches (271 points)
- Total cell count: 53 million



- The commercial CFD code STAR-CCM+ is used for all simulations. This code is a cell-centered finite-volume solver using cells of arbitrary polyhedral shape.

- A compressible (pressure-based) implicit unsteady segregated solver is used.
- Hybrid numerical scheme (Travin et al. 2002) blending second-order upwind for RANS regions (and far-field) and then a 2nd order central differencing scheme in LES regions (**explained later**)

- 2nd order upwind for the turbulent quantities (DLR showed this is important for a three-element airfoil)

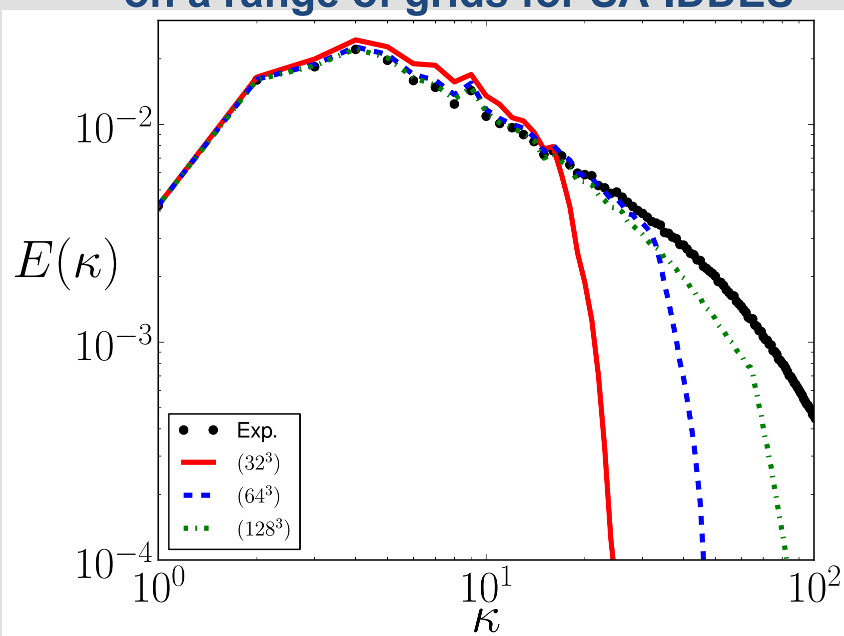
- An implicit 2nd order temporal scheme is used with a non-dimensional time step of $t * U/c = 1.46 \times 10^{-4}$, which ensured a convective CFL number below one and convergence per time step.

- SST IDDES (Improved Delayed Detached-Eddy Simulation)

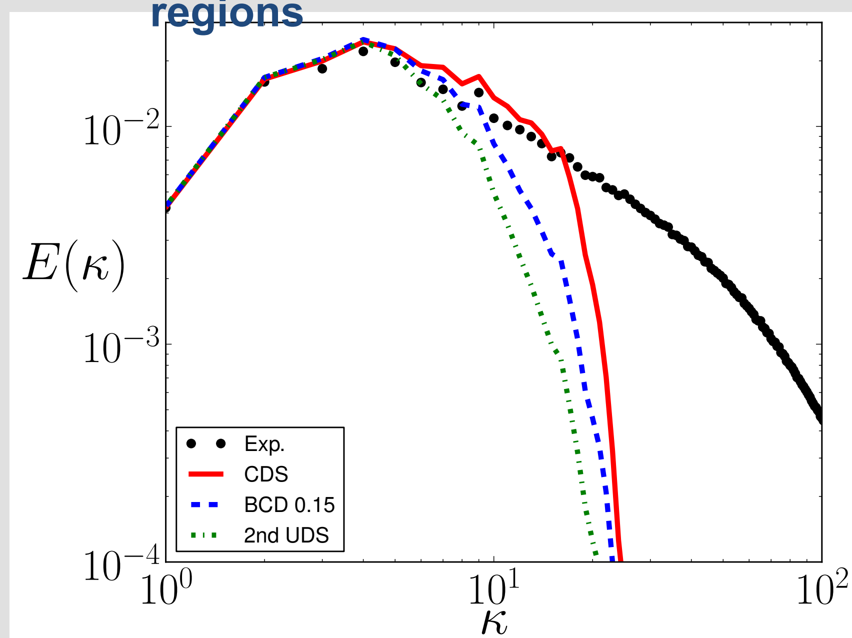
- No-slip conditions are prescribed at the airfoil walls with periodic conditions at the lateral boundaries.
- Non-reflecting farfield boundary conditions are used for all remaining outer boundaries.
- All simulations were initialized using a converged steady RANS solution, after which six flow-throughs (t * U/c) were completed (with ramping of the time-step) before time-averaging began for a further 13 and 7 flow-throughs for the structured and unstructured grids respectively.

- Level of dissipation from the model and numerics have a profound influence on hybrid RANS-LES simulations (Ashton et al. 2011).
- Calibration of the SA and SST based DDES/IDDES models conducted using Decaying Isotropic Turbulence (DIT). **(SA-IDDES shown here)**

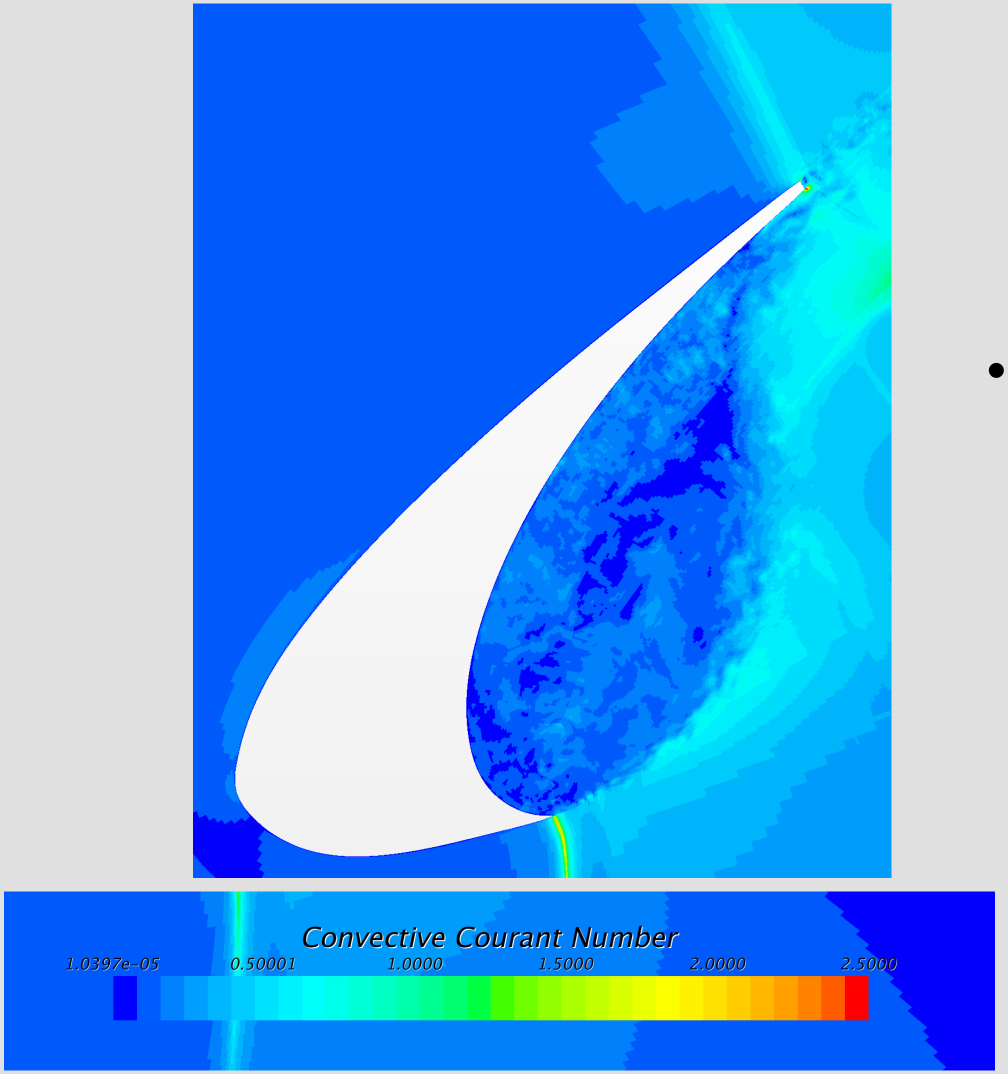
C_{DDES}=0.65 gives suitable dissipation on a range of grids for SA-IDDES



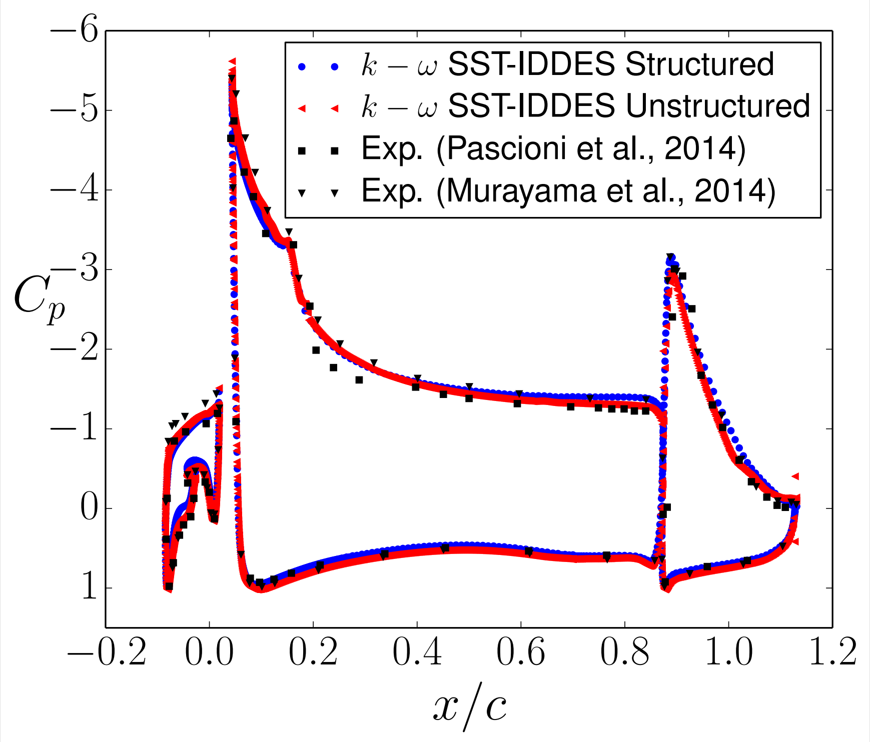
Pure CDS is crucial for LES regions



Results



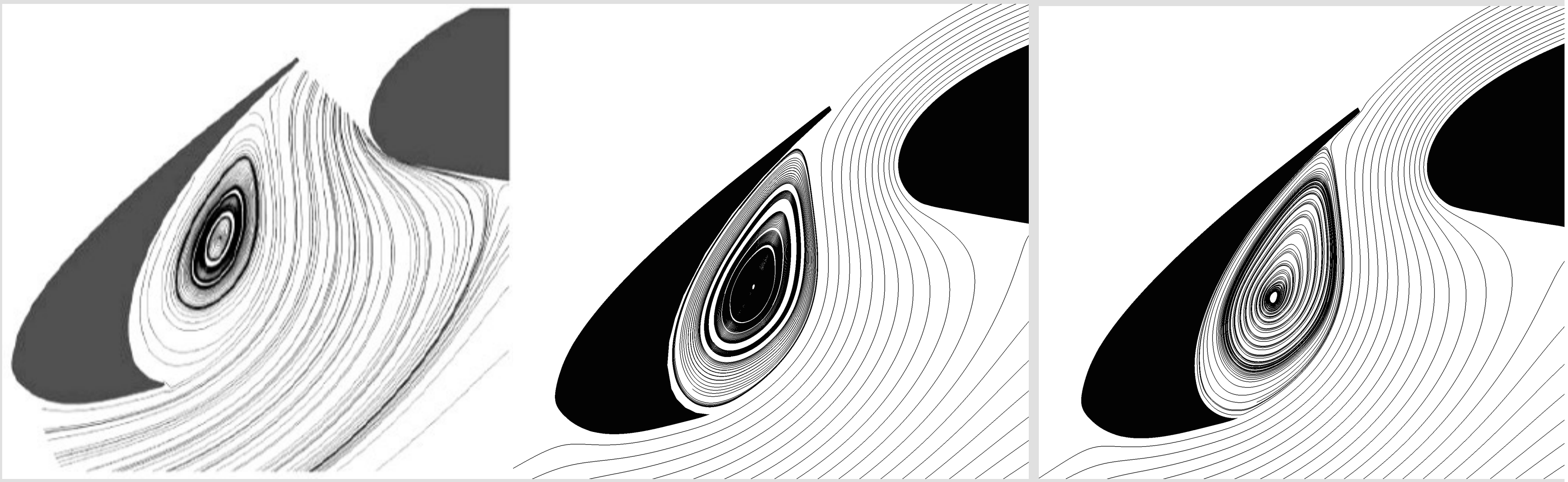
- Convective Courant number is below 1 in the LES regions throughout the flow ensuring as little numerical dissipation from the time scheme as possible.



- Structured grid agrees well with BANC Median results
- Unstructured has greater separation from the flap giving higher C_D
- Overall agreement is reasonable

Model	C_L	C_D	$C_{L,s}$	$C_{L,m}$	$C_{L,f}$	Impingement distance
BANC III Workshop Median[2]	2.64	n/a	n/a	n/a	n/a	16.6 mm
SST IDDES (Structured)	2.631	0.135	0.089	2.058	0.485	16.5 mm
SST IDDES (Unstructured)	2.648	0.184	0.110	2.081	0.455	17.0 mm

Table 2. Predicted aerodynamics properties.

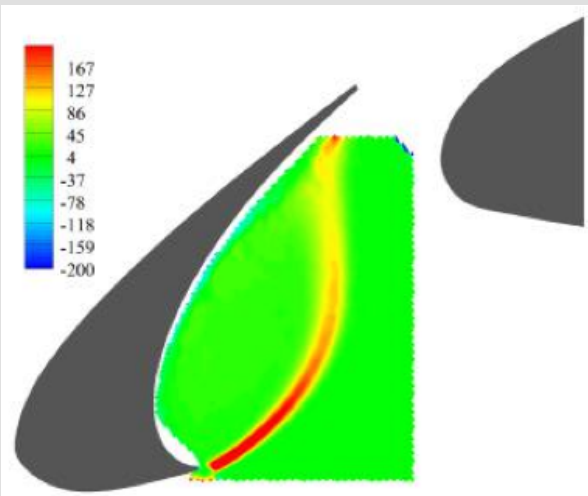


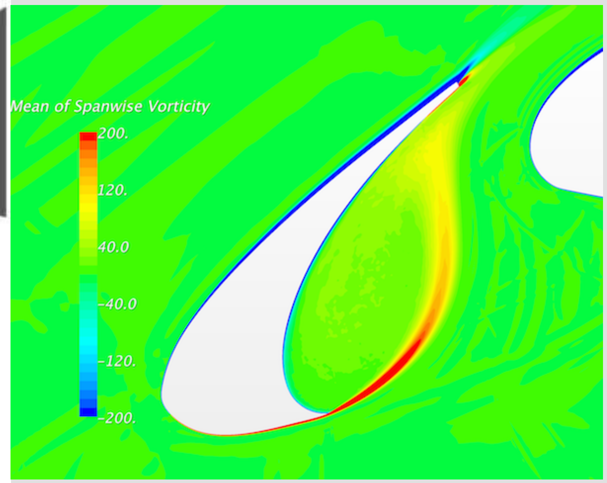
Ex
p

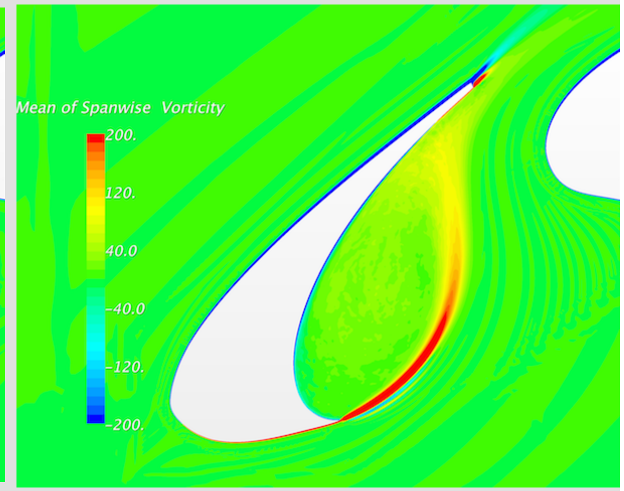
Structured

Unstructured

- Mean slat cove region is predicted well by both grid types





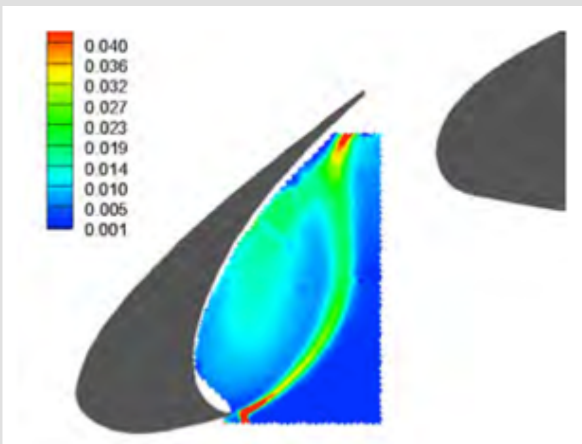


Ex
p

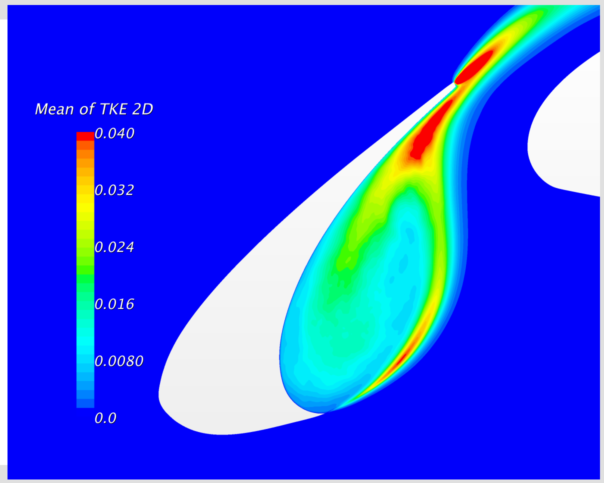
Structured

Unstructured

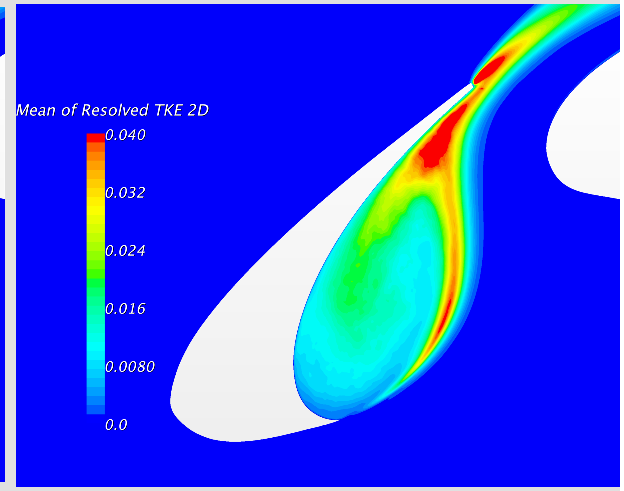
- Mean spanwise vorticity also well predicted by both grid types
- Slightly thicker shear layer from unstructured grid



Experiment



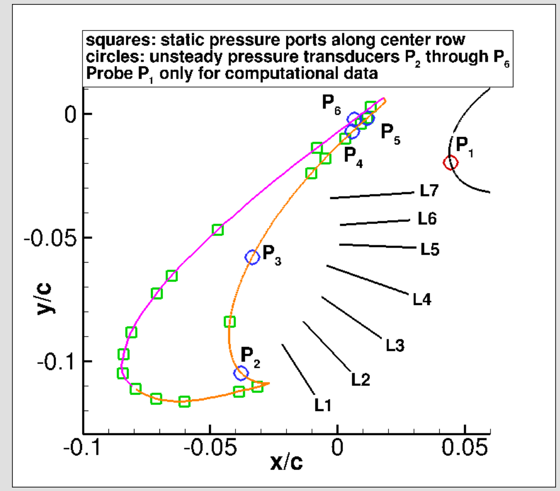
Structured

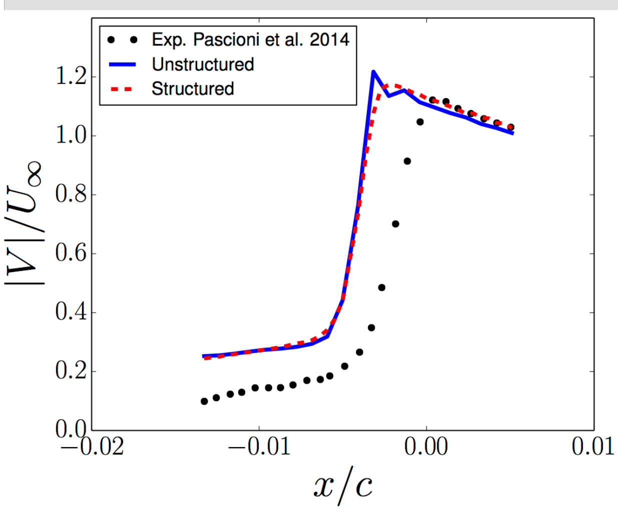


Unstructured

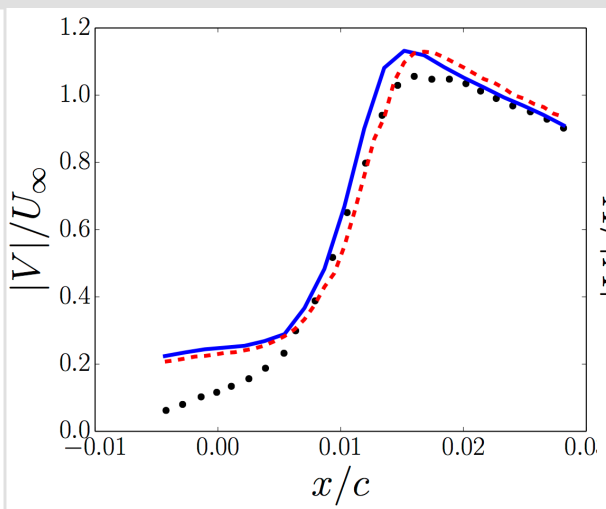
- Similar TKE although PIV resolution and coverage limits conclusions.
- Note the lack of TKE in the beginning of the shear-layer

- Largely good agreement for these mean quantities

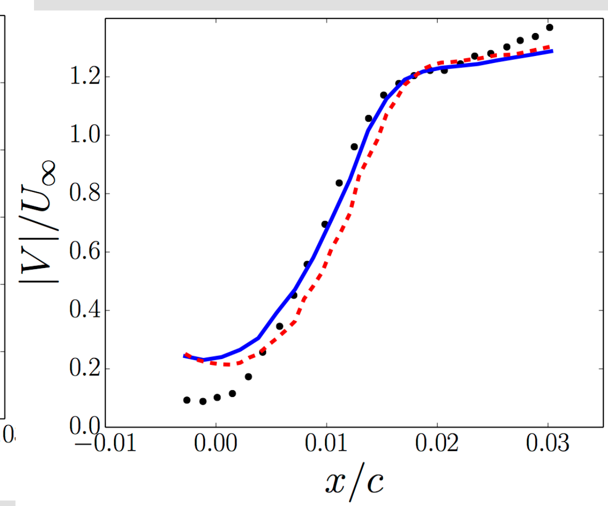




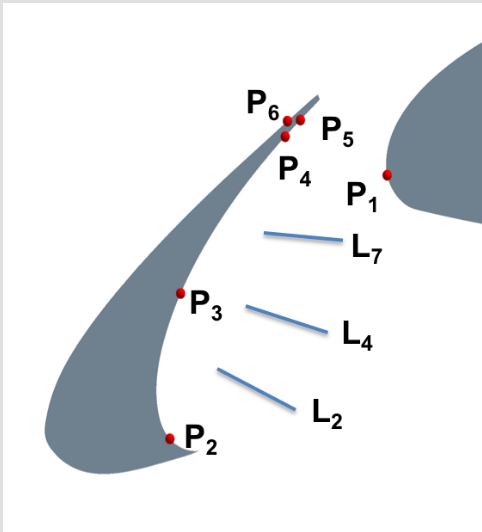
L2

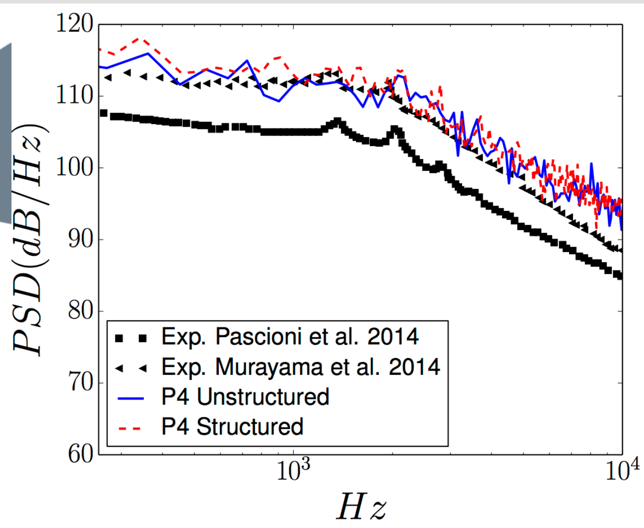


L4

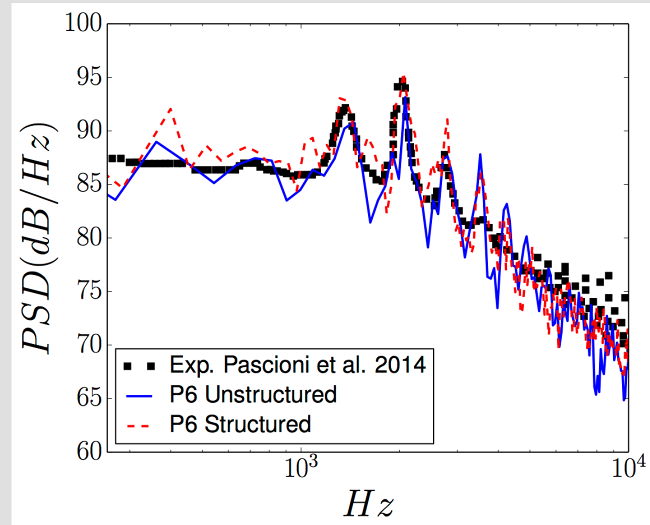


L7





P4



P6

- Generally good agreement between CFD and Exp
- However unstructured signal more noisy signal

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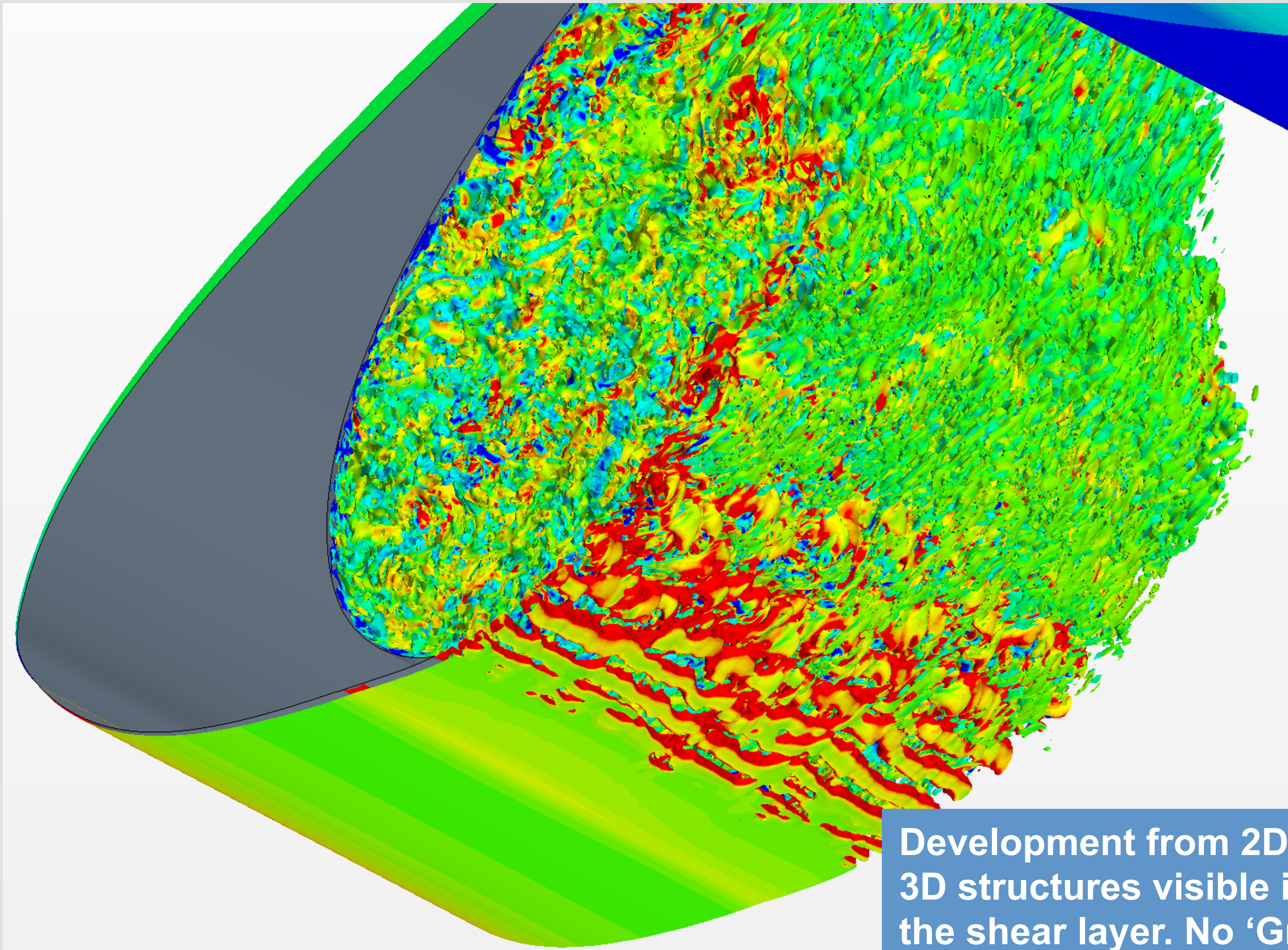
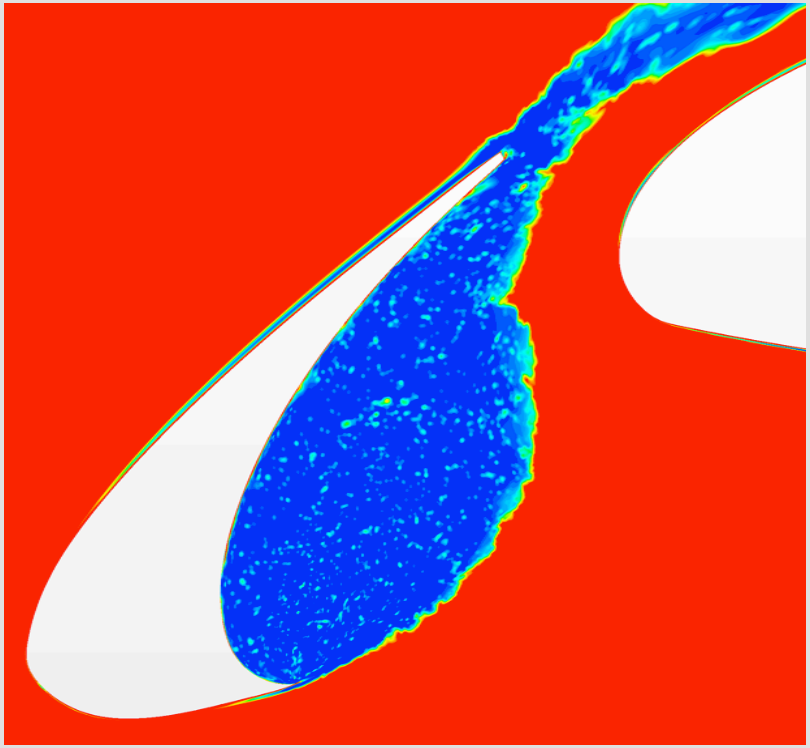
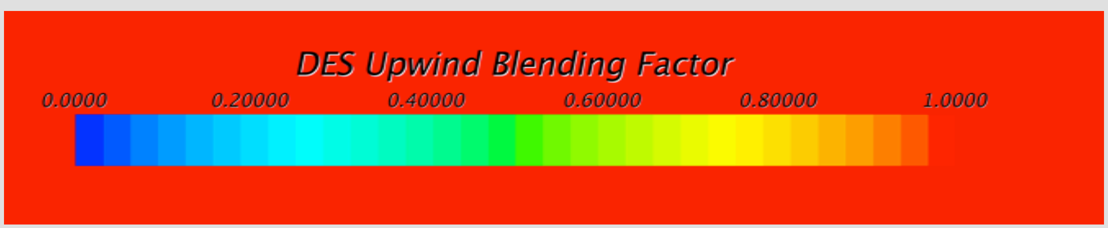


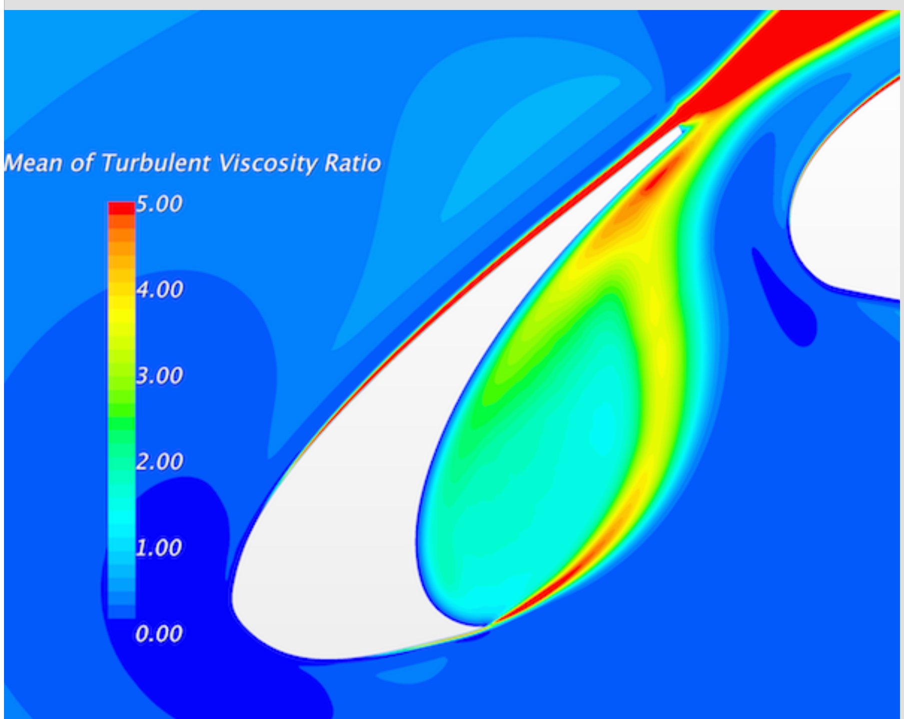
Development from 2D to 3D structures visible in the shear layer. No 'Grey-area' problem.



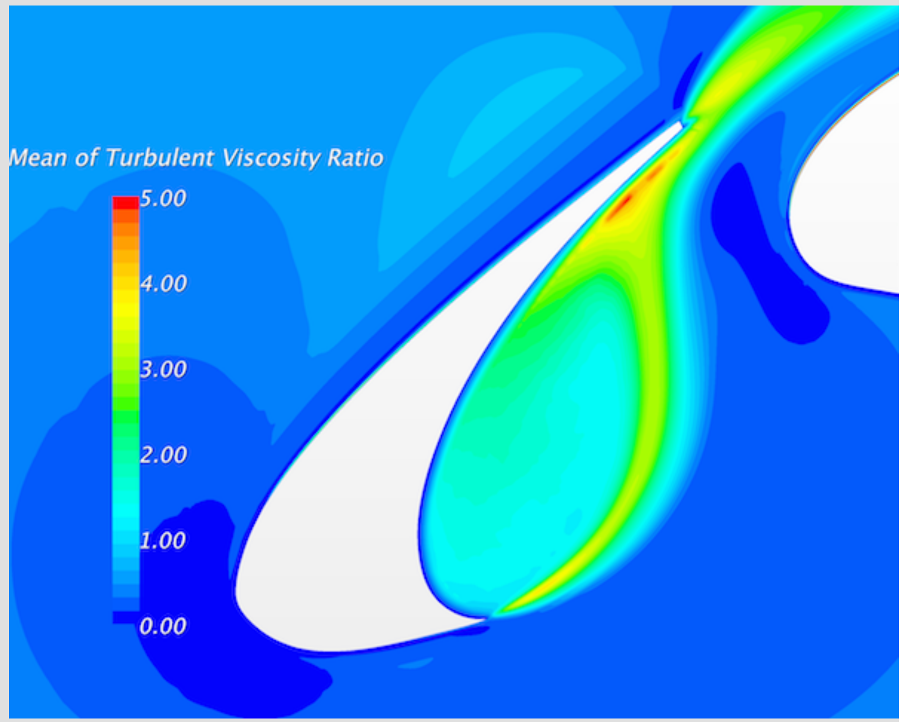
Pure CDS is being applied in the important slat cove region where LES mode is active (Blue). 2nd order upwind very near the wall and in the outer regions (Red).



- Signs of problems..
- Much lower Turbulent Viscosity on unstructured grid

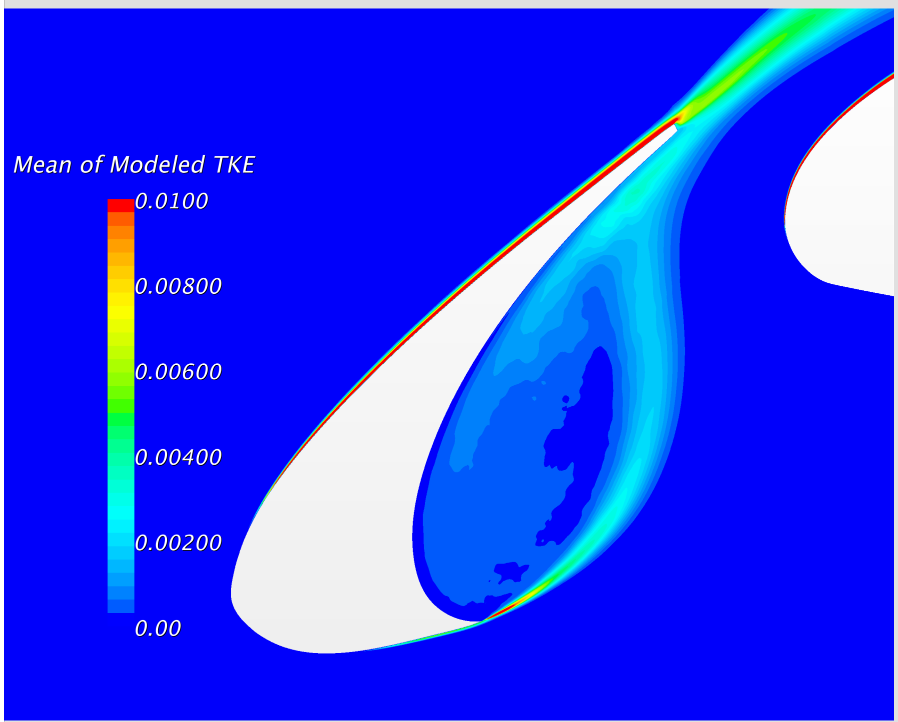


Structured

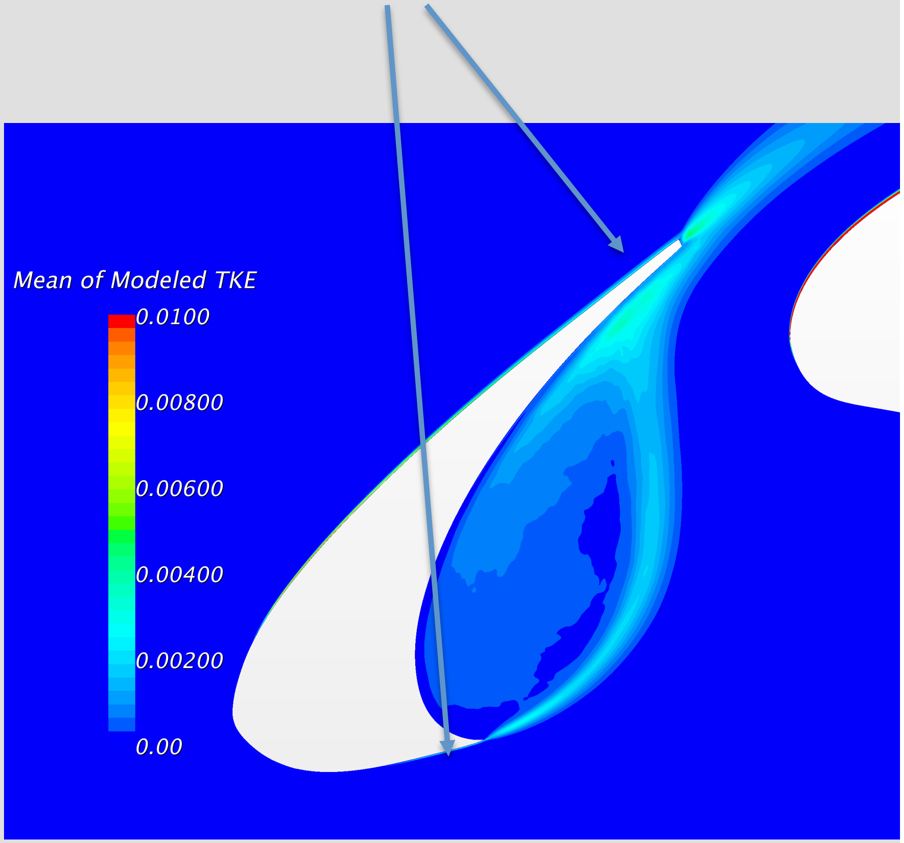


Unstructured

- Unstructured grid has very little modeled turbulence



Structured



Unstructured

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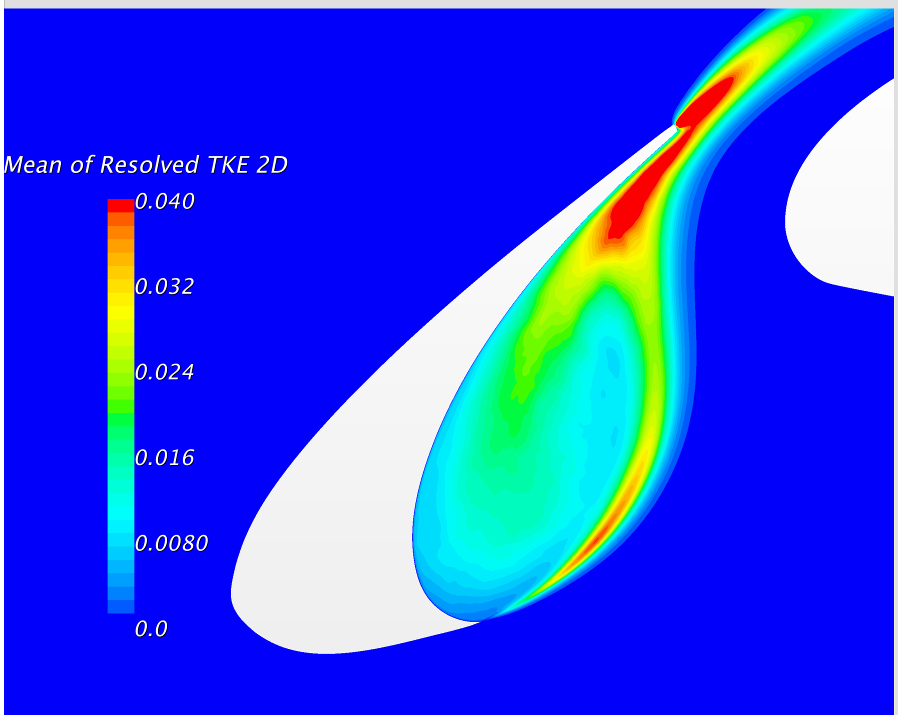
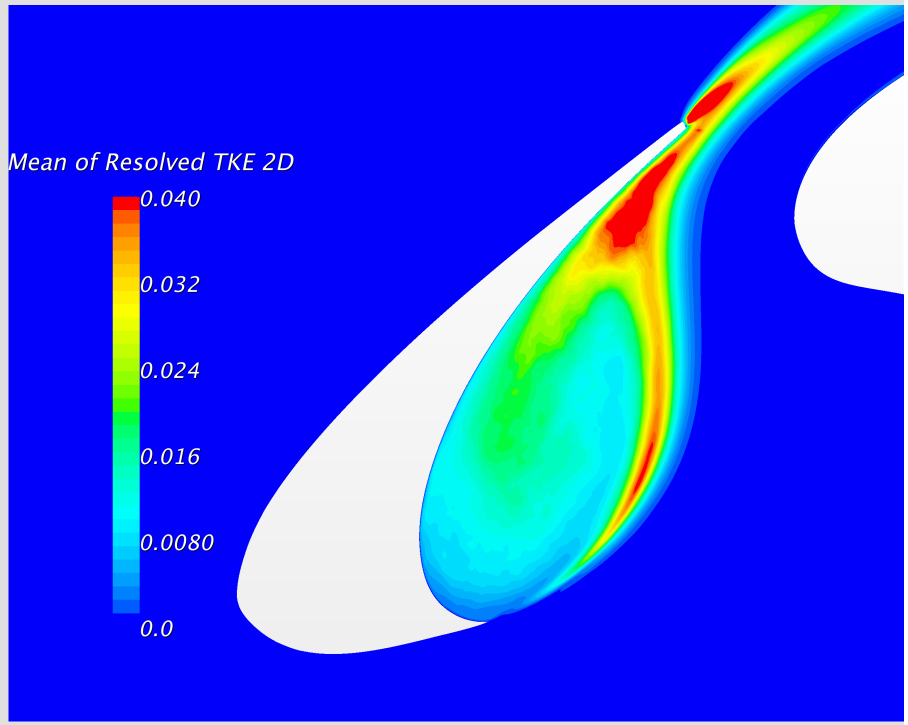
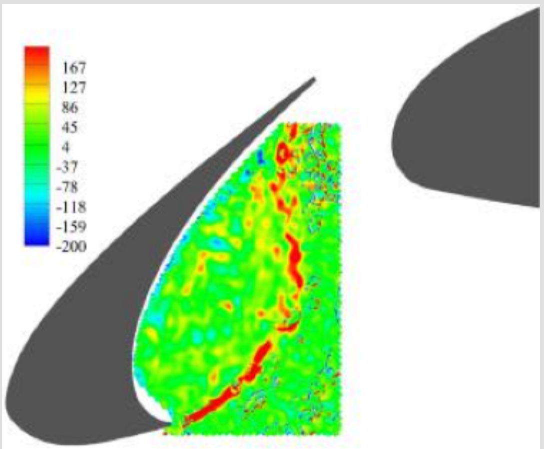
With no resolved TKE in the upper-side of the slat or the leading-edge



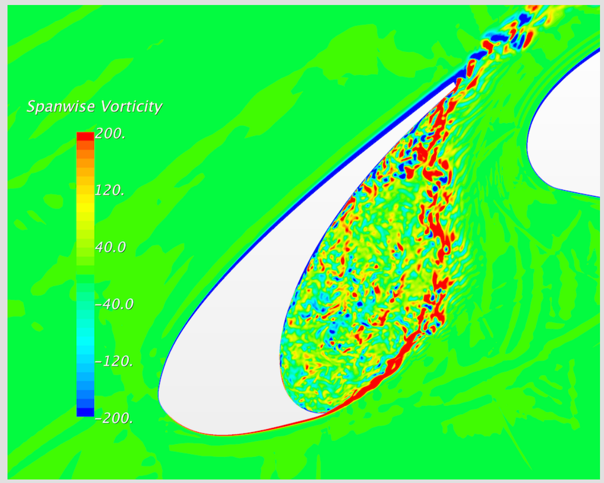
Structured



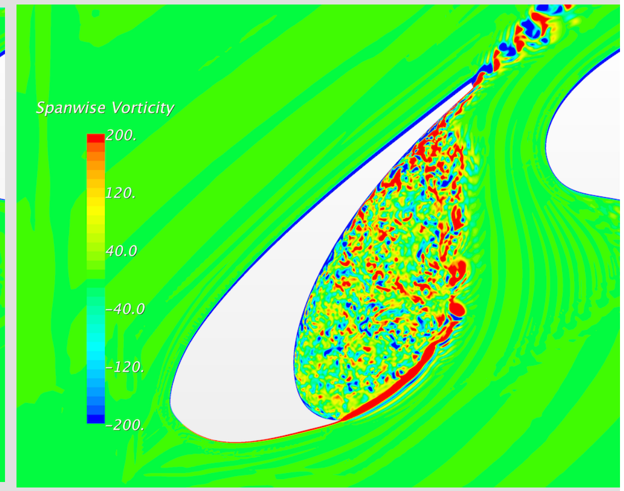
unstructured



Experiment

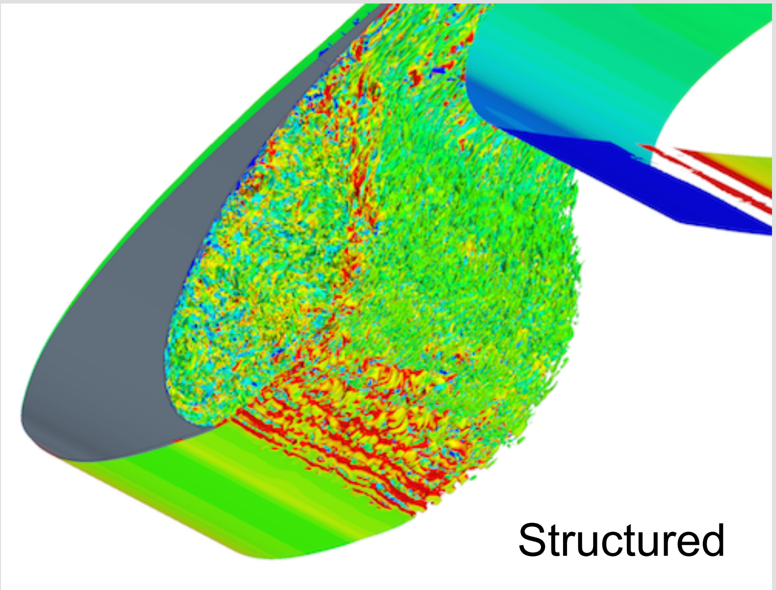


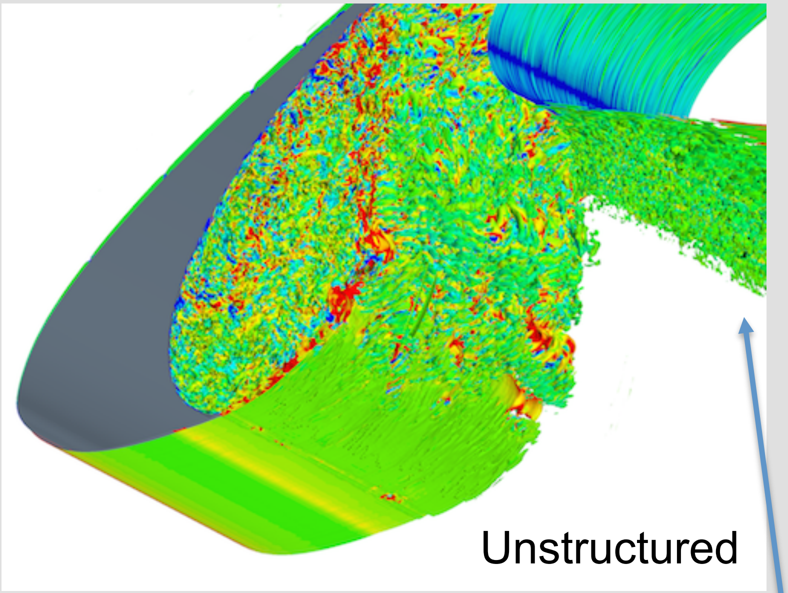
Structured



Unstructured

- Good agreement between structured and PIV
- Note the initial unstructured shear layer is delayed





- Note the activation of LES content on the lower-side of the wing

- Initial feelings were that this was a mesh quality issue
- Unstructured grid wasn’t as good quality as the structured etc

- Partly true – transitions between cells isn’t as smooth and there is a lack of resolution in the shear-layer.

- However deeper investigation + conversations with other researchers found something extra

- Shielding function breakdown.

- Spalart (1997) developed Detached Eddy Simulation (DES) where the decision between RANS and LES is made by looking at the grid size.
- Rationale is that the Spalart Allmaras solves a single equation for a modified turbulent viscosity. The length scale in this equation is the wall-distance, and when we take equilibrium assumption: (production=dissipation), we find:
- $\boldsymbol{v \approx S\, d^2}$
- We can then note that this is the same form as the Sub-grid scale models like the Smagorinsky model i.e $\boldsymbol{v \approx S \Delta^2}$
- Thus we can replace ***d*** by a length proportional to $\boldsymbol{\Delta}$

- Thus to calculate the choice between LES and RANS, this length is based upon the minimum of the RANS length scale (d) and the LES length scale (grid spacing, Δ)
- $d_{DES} = min(d, C_{DES}\Delta)$
- The only modification of the Spalart-Allmaras RANS model to use in DES mode is to replace the wall-distance term by the above equation.
- The constant C_{DES} must be calibrated in the same way as the Smagorinsky constant, this will be shown in later slides.
- Thus for standard DES with the SA model, the mesh itself decides where RANS or LES will be.
- The LES region should have the same grid resolution as a LES (no coarser), but the region close to the wall where the RANS mode should be active (as wall distance becomes larger) can have a RANS-like resolution)

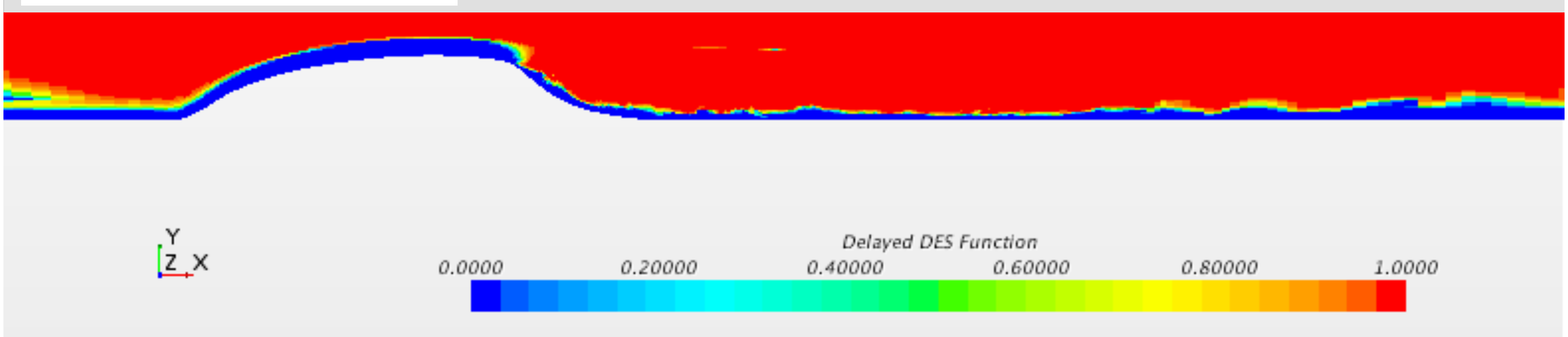
- The saving compared to a LES is therefore that the RANS region can have non-isotropic cells and does not need a LES resolution close to the wall. Larger time step as a result from not requiring as small cells.
- Common misconception is that DES has a LES and RANS solver, it is the same model. The justification is that a RANS models such as SA produces a turbulent viscosity which is used in the momentum equations and so does a Smagorinsky SGS LES model. The momentum equations *do not know* where this came from, thus allowing this viscosity to come from a eddy-viscosity RANS models which reduces the turbulent viscosity when the grid gets finer.

- The original DES paper was only for the Spalart Allmaras model (Spalart co-creator of this model, and the model of choice for his employer, Boeing!)
- Travin et al. (2000) illustrated that this approach could be extended to other models such as the SST model.
- For the SST model, the length scale was chosen to be replaced in the destruction term of the *k* equation (simplest method and has carried forward):
- $\beta k\omega=\varepsilon=k^{3/2}/L_{DES}$
- Where in a similar fashion to SA model, $L_{DES}=\min(L_{RANS}, C_{DES}\Delta)$, where $L_{RANS}=k^{1/2}/\omega$
- Thus DES can be applied to most RANS models using the 'standard' approach.

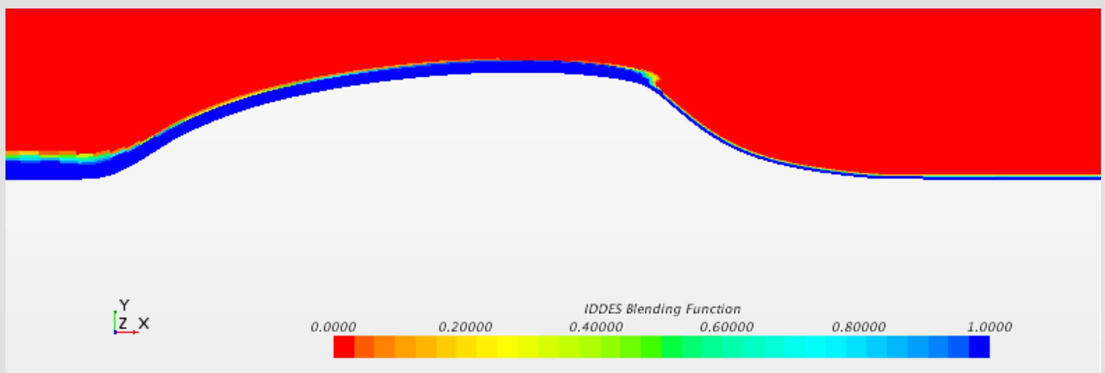
- In Detached Eddy Simulation (DES), the only control over the RANS and LES zones is through the grid.
- Problems can arise where the near-wall grid is refined so much that the grid spacing (filter width) becomes smaller than the RANS length scale (wall-distance if using SA model). At this point the model would switch to LES mode. However the grid is not refined **enough** for LES.
- Thus too little modeled turbulence from RANS model and too little resolved turbulence. Termed Modelled Stress Depletion (MSD). This can induced early separation due to too low turbulence mixing.

- Solution was to shield the boundary layer and enforce RANS model in these regions.
- First attempt was by Menter to use his F_2 blending function from the SST model.
- This worked but requires the F_2 blending function which is specific to the SST model, thus not a general solution.
- Spalart et al. (2003) derived a new, more general blending function, which formed the basis for **Delayed** Detached-Eddy Simulation (DDES).
- R_d=1 near the wall and 0 towards the edge of the boundary layer.

$$r_{\mathrm{d}} \equiv \frac{\nu_t + \nu}{\sqrt{U_{i,j}U_{i,j}}\kappa^2 d^2}, \quad f_{\mathrm{d}} \equiv 1 - \tanh([8r_{\mathrm{d}}]^3), \qquad L_{DDES} = L_{RANS} - f_d \max(0, L_{RANS} - C_{DDES}\Delta)$$



- Aim to provide wall-modelled LES capability i.e LES inside the boundary layer. But still RANS in the viscous region. Bridge the gap between wall-resolved LES (LES all the way to the wall) and current DDES-like approaches where RANS covers whole boundary layer.
- IDDES (2008) proposed to have combine both WMLES and normal DDES.



- IDDES

$$L_{IDDES} = \tilde{f}_d L_{RANS} + (1 - \tilde{f}_d) L_{LES}$$

Substitute into RANS equations as DES

$$\begin{aligned} L_{LES} &= C_{DES}\Delta_{IDDES} \\ L_{RANS} &= \sqrt{k}/c_{\mu}\omega \end{aligned}$$

SST here but wall-distance for SA

$$\begin{aligned} \Delta_{IDDES} &= min\left(max\left[C_w d_w, C_w h_{max}, h_{wn}\right], h_{max}\right) \\ h_{max} &= max(\Delta x, \Delta y, \Delta z) \end{aligned}$$

DES Length Scale

Empirical constant = 0.15

Wall-distance

Wall-normal grid spacing

The purpose of this is to reduce the filter width near the wall which in turn lowers the turbulent viscosity and resolves more of the boundary layer.

- IDDES – shielding functions

$$\tilde{f}_d = max\left[(1 - f_{dt}), f_B\right]$$

Blends between a DDES and WMLES mode

$$f_{dt} = 1 - tanh[(20r_{dt})^3].$$

$$r_{dt} = \frac{\nu_t}{\sqrt{U_{i,j}U_{i,j}}\kappa^2 y^2}$$

Modified DDES shielding (only nu_t on top)

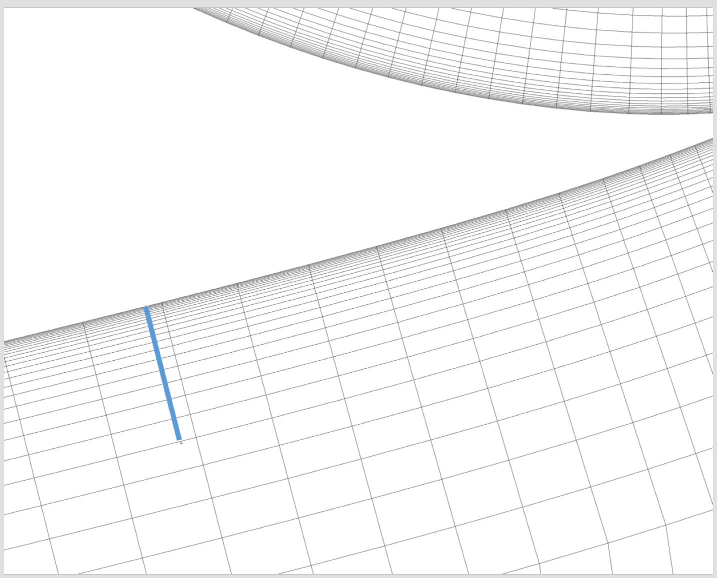
$$f_B = min[2exp(-9\alpha^2), 1.0]$$

WMLES Blending function

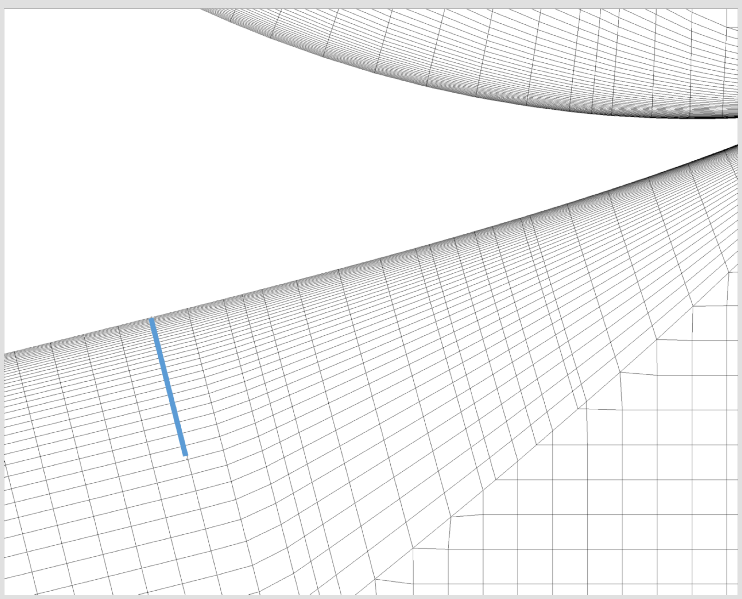
The idea is to blend between a DDES formulation when there is nu_t e.g without inflow turbulence, and then move to a WMLES formulation when there is unsteady content.

- IDDES – shielding functions

Lets look at one locations in the slat boundary layer



Structured

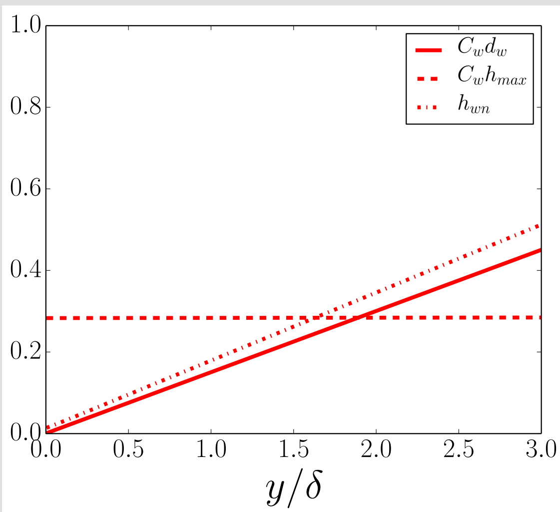


Unstructured

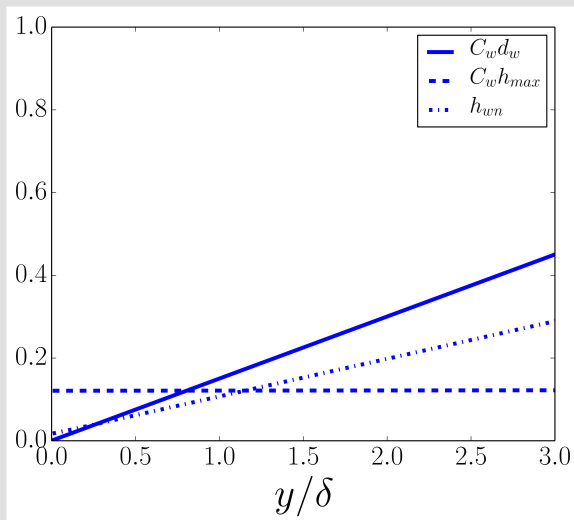
- IDDES – shielding functions

$$\Delta_{IDDES} = min\left(max\left[C_w d_w, C_w h_{max}, h_{wn}\right], h_{max}\right)$$

$$h_{max} = max(\Delta x, \Delta y, \Delta z)$$



Structured



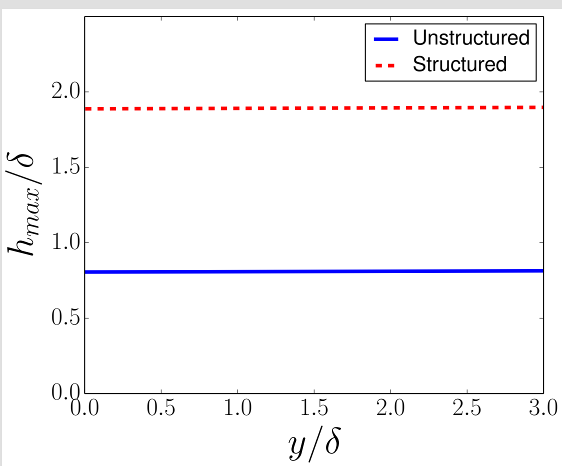
Unstructured

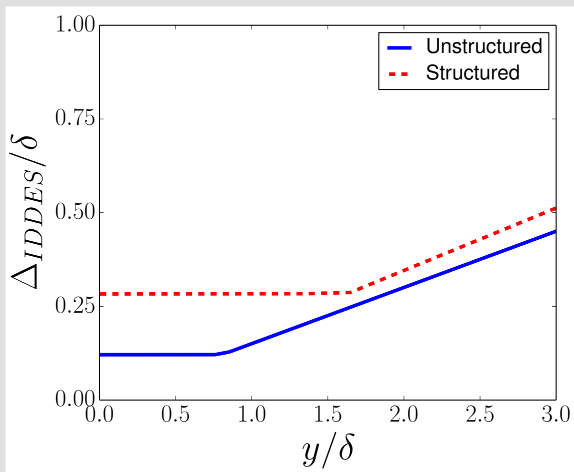
C_w H_{max} is the maximum within the boundary layer

- IDDES – Filter width

$$\Delta_{IDDES} = min\left(max\left[C_w d_w, C_w h_{max}, h_{wn}\right], h_{max}\right)$$

$$h_{max} = max(\Delta x, \Delta y, \Delta z)$$





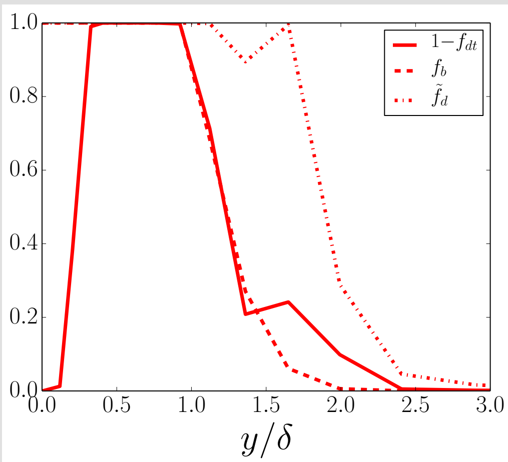
Both grids have the same y +, z+ but x+ is smaller for unstructured.

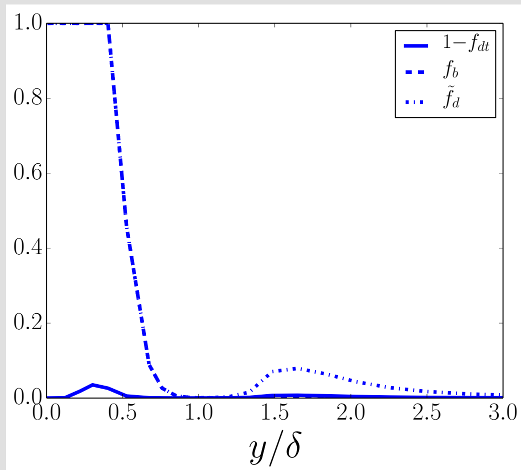
Due to streamwise spacing being smaller

- IDDES – Shielding function

$$\tilde{f}_d = max\left[(1 - f_{dt}), f_B\right]$$

Shielding function covers only half of boundary layer for the unstructured grid



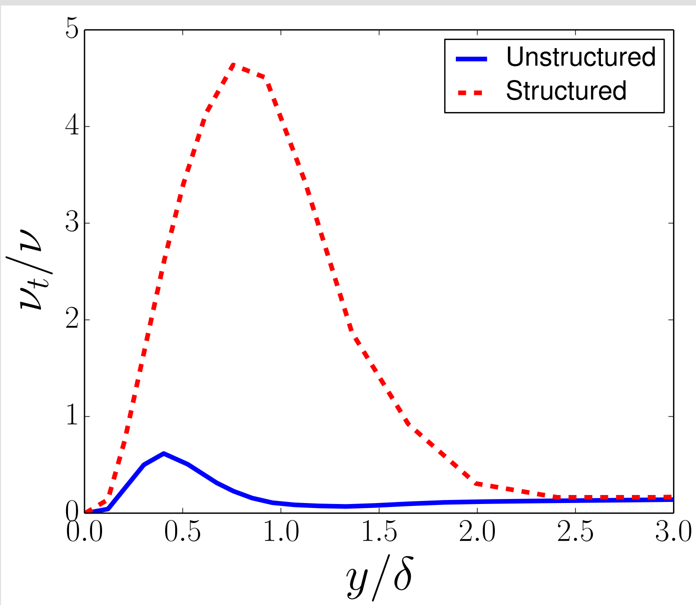


Structured

Unstructured

- IDDES – Shielding function

There is a feedback mechanism where lower nu_t drives down r_d, meaning fd_t becomes 1.



$$f_{dt} = 1 - tanh[(20r_{dt})^3].$$

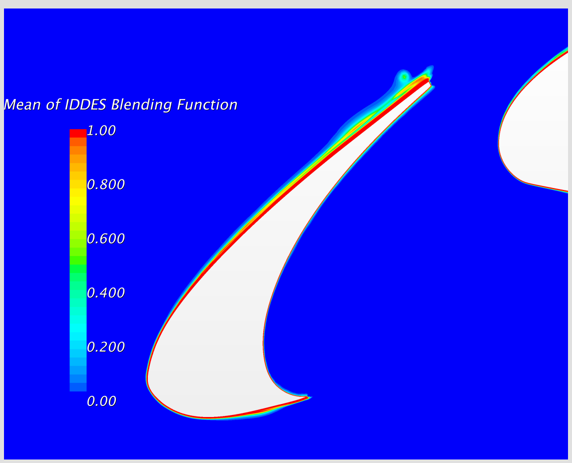
$$r_{dt} = \frac{\nu_t}{\sqrt{U_{i,j}U_{i,j}\kappa^2 y^2}}$$

WMLES mode e.g f_b is only supposed to kick in when there is unsteady inflow e.g nu_t is low.

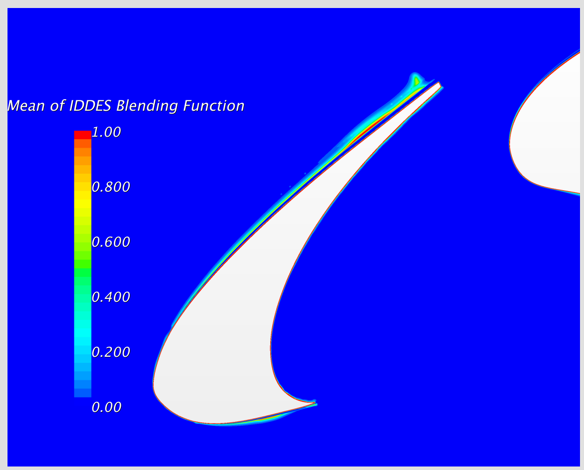
- IDDES – shielding functions

$$\Delta_{IDDES} = min\left(max\left[C_w d_w, C_w h_{max}, h_{wn}\right], h_{max}\right)$$

$$h_{max} = max(\Delta x, \Delta y, \Delta z)$$



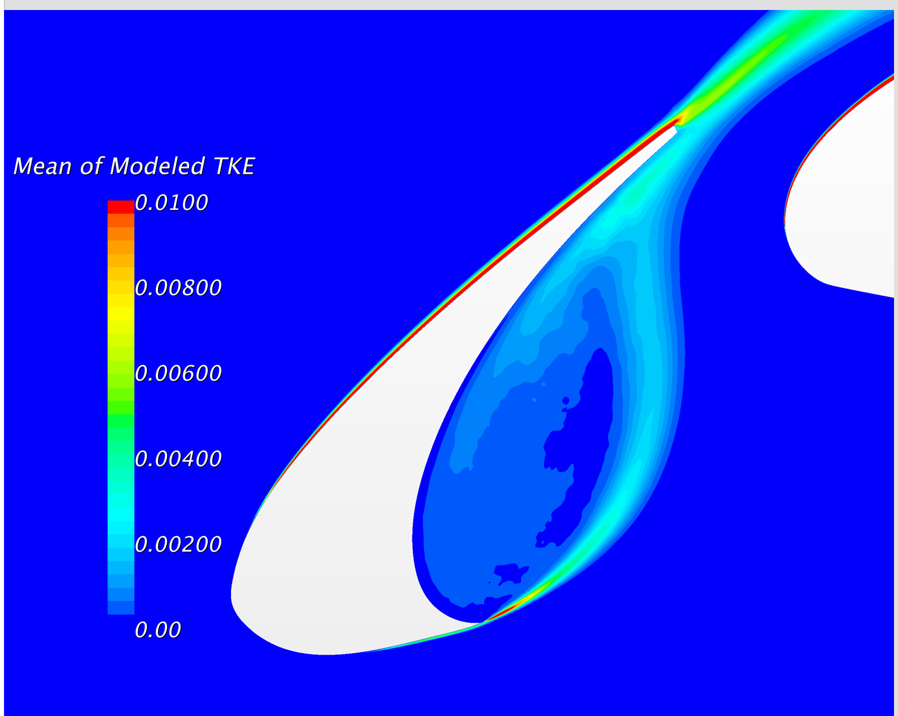
Structured



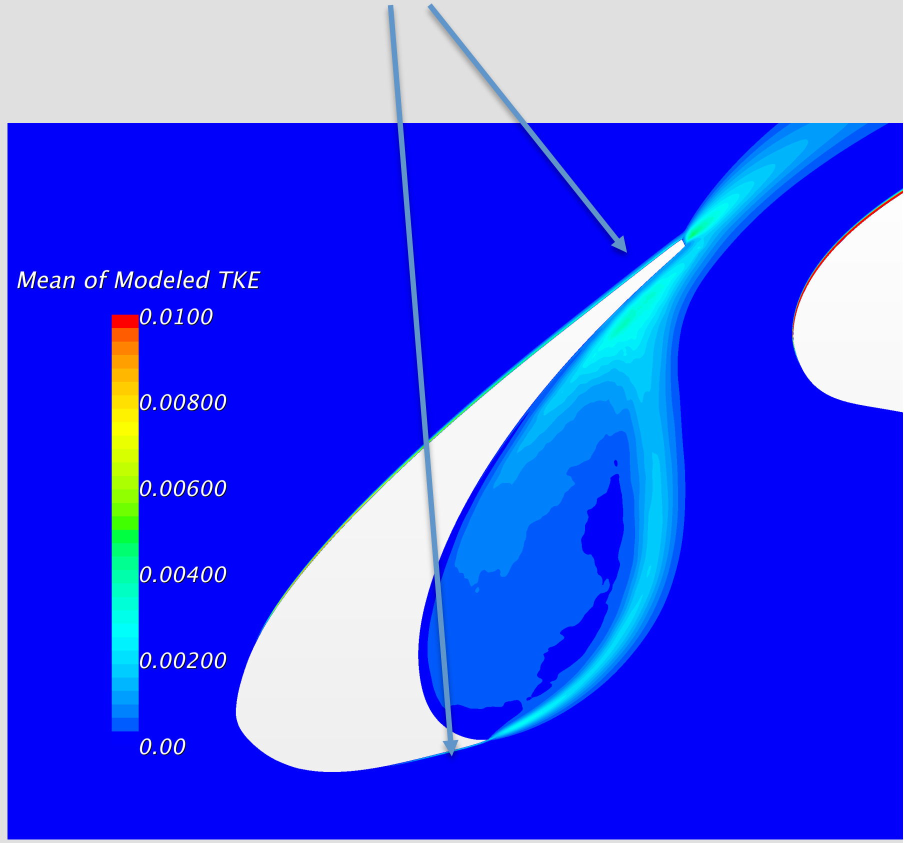
Unstructured

IDDES blending function

- Unstructured grid has very little modeled turbulence

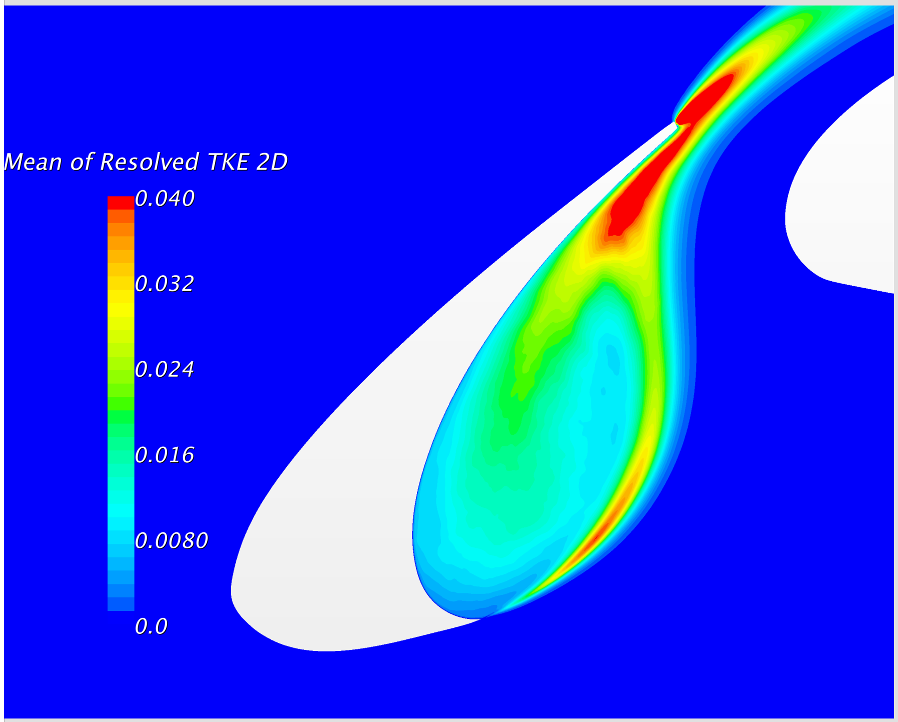


Structured

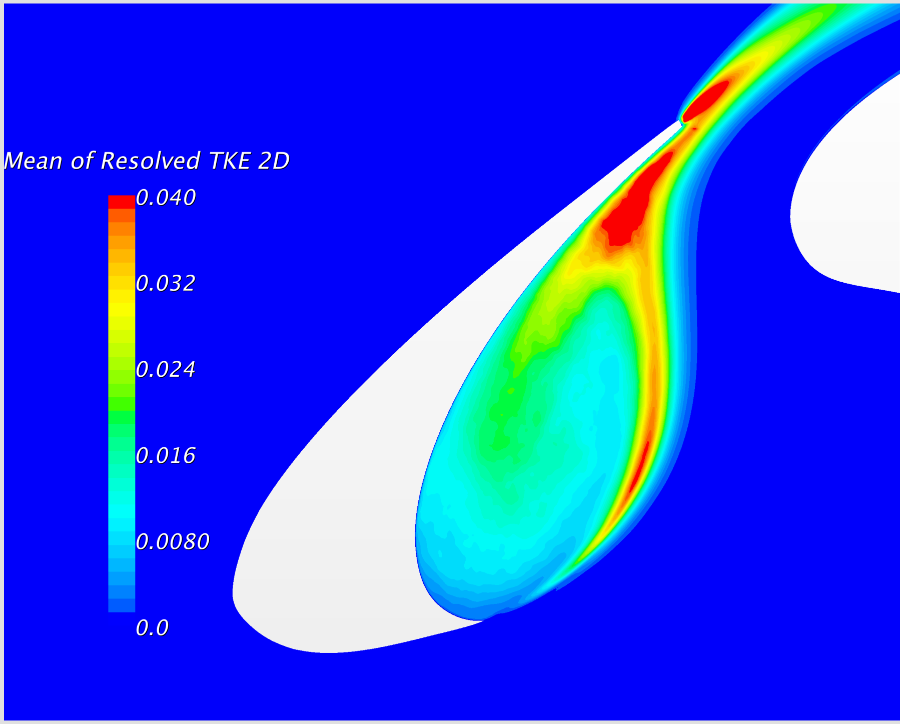


unstructured

With no resolved TKE in the upper-side of the slat or the leading-edge



Structured



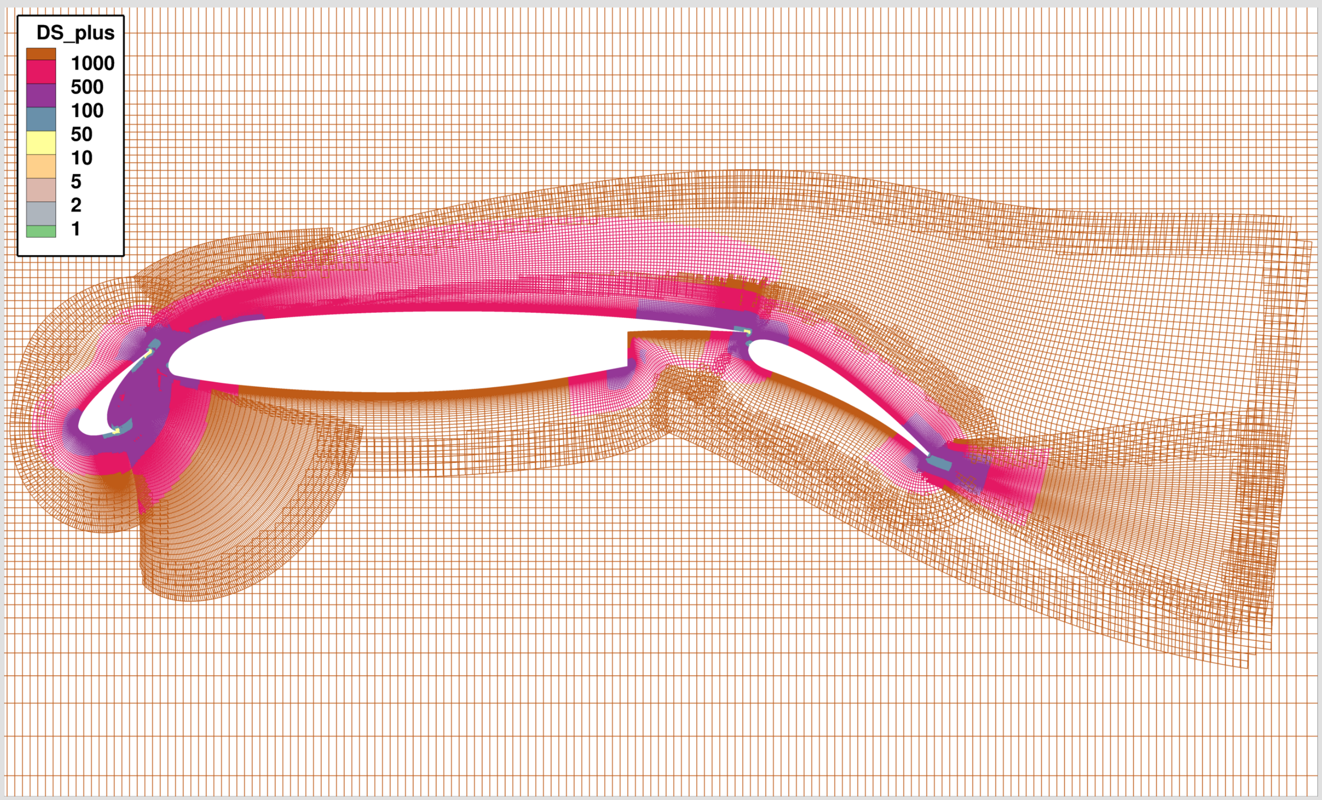
unstructured

Extra grid refinement in the streamwise direction has caused the f_d function to break down and allow WMLES to kick in.

Not sufficient grid resolution for inflow for this.

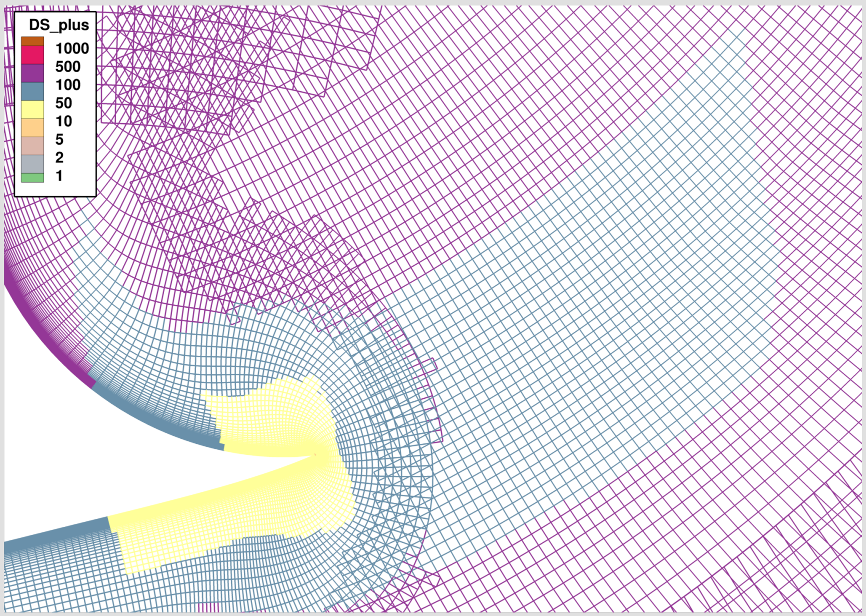
But what about DDES?

- Similar issues found with NASA's LAVA Curvilinear code
- Overset grids – High order numerics, SA-DDES model – i.e different than unstructured SST-IDDES!

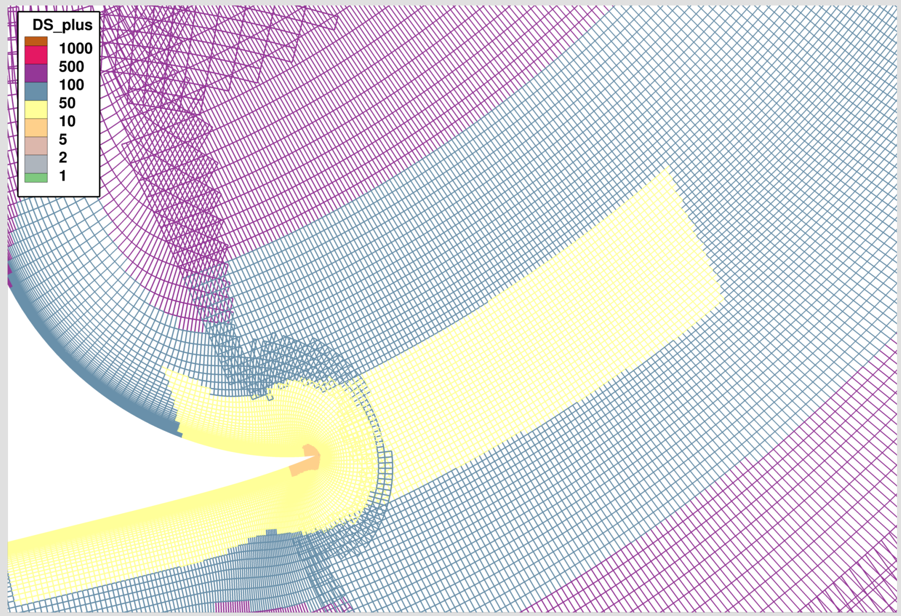


- Example of two grids, with greater refinement. Note the streamwise non-dimensional spacing ~ 50

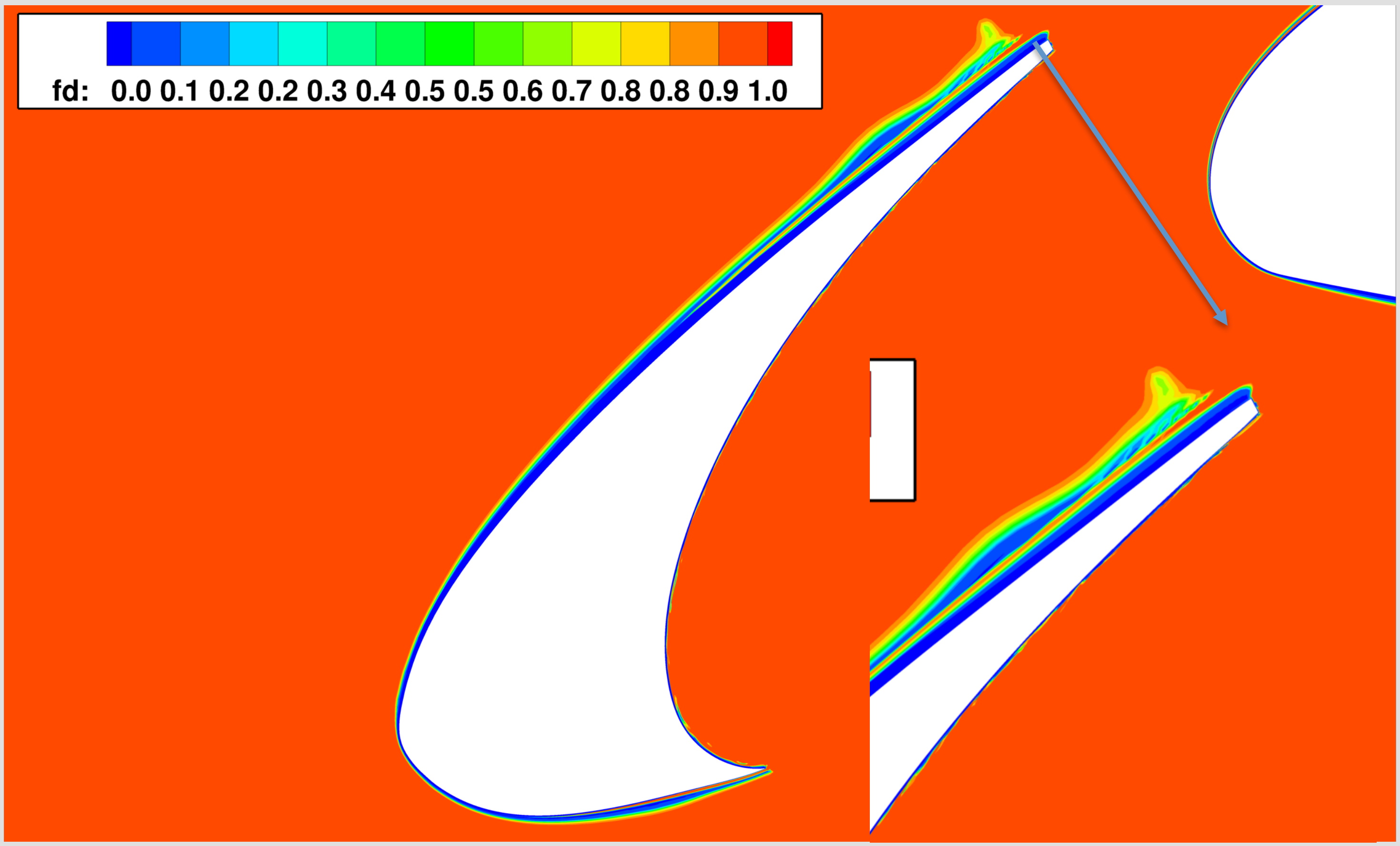
32.5 million grid points (grid 1)



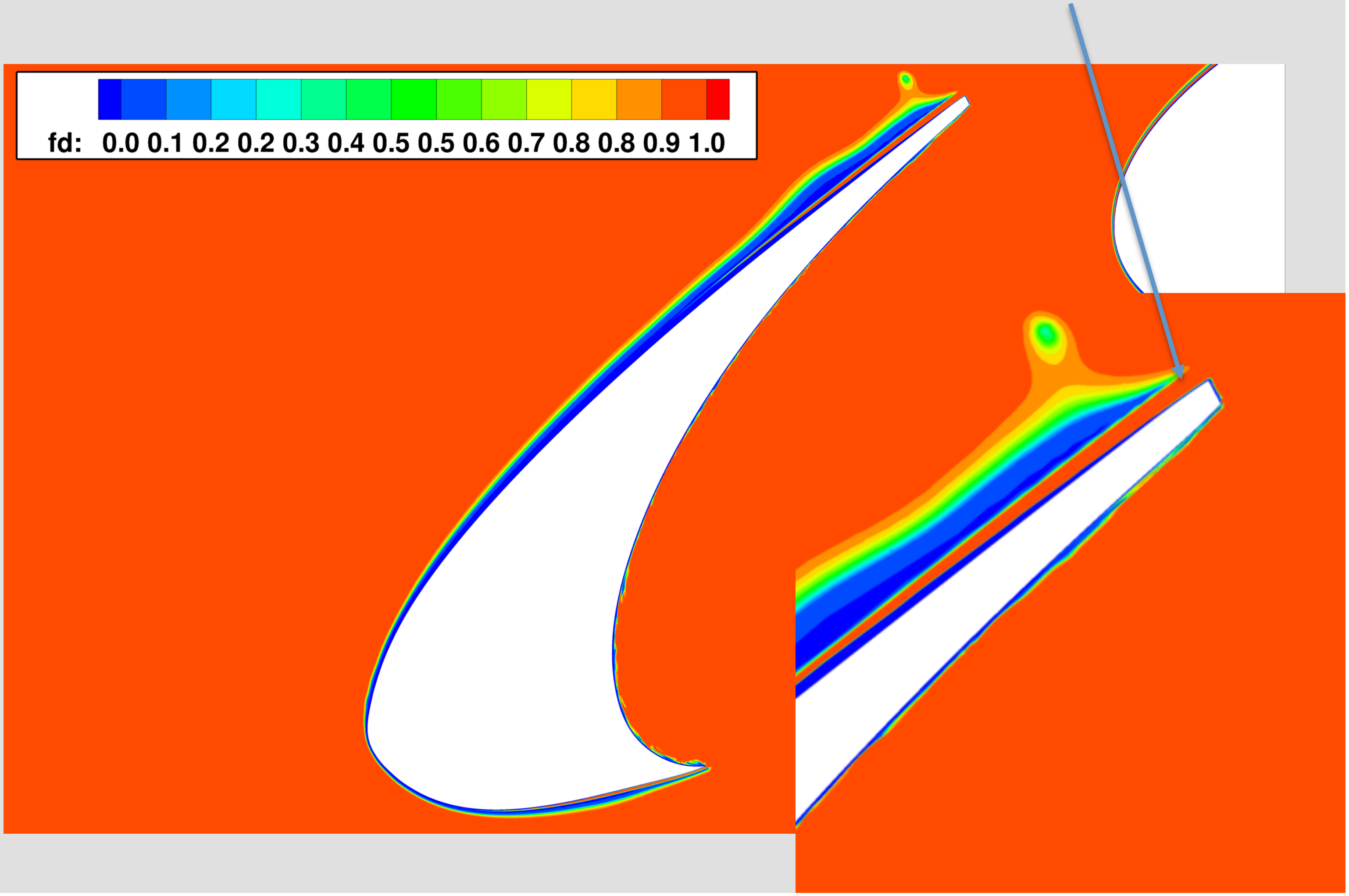
78.1 million grid points (grid 2)



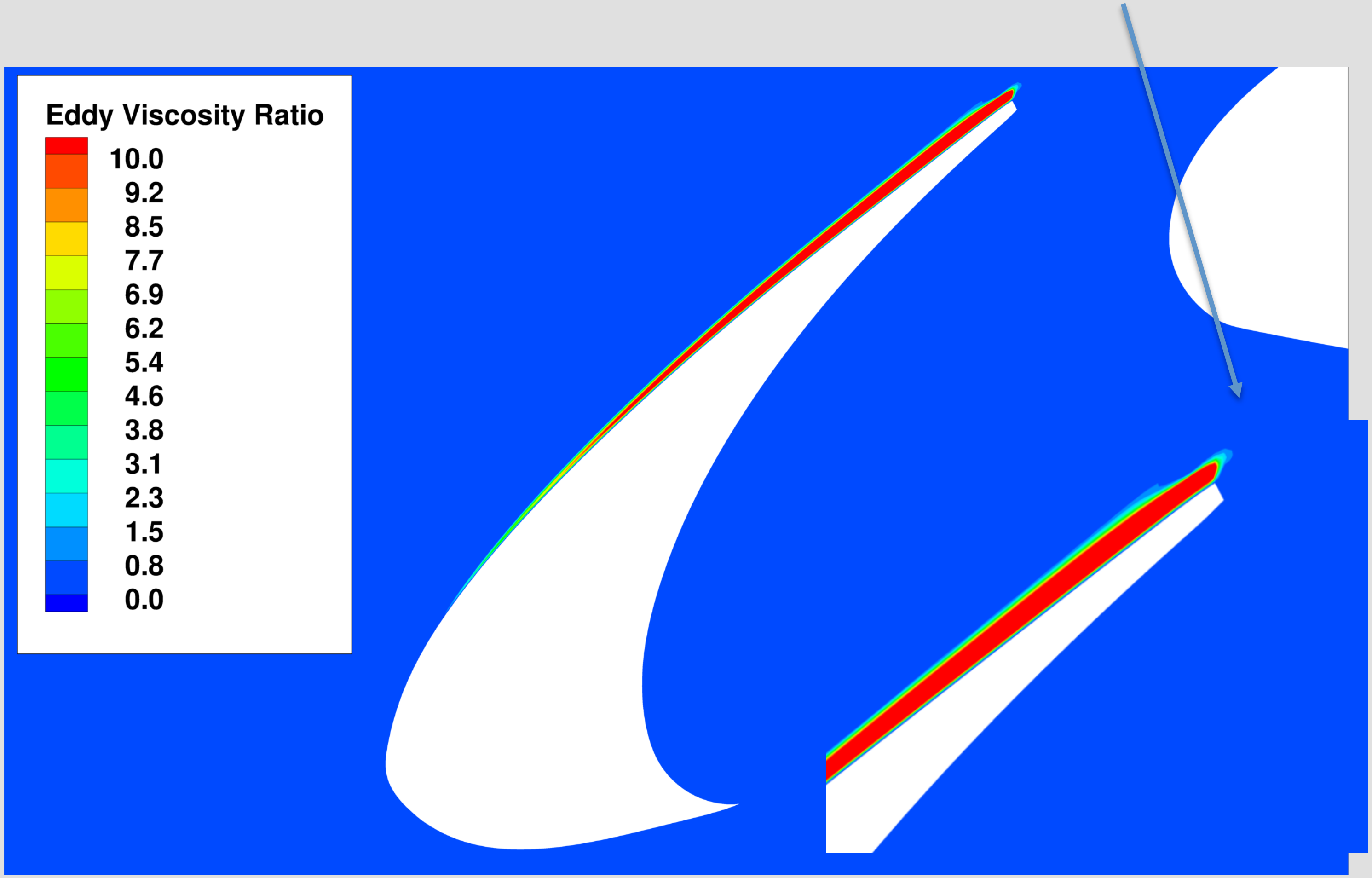
- Grid 1 – Normal F_d function



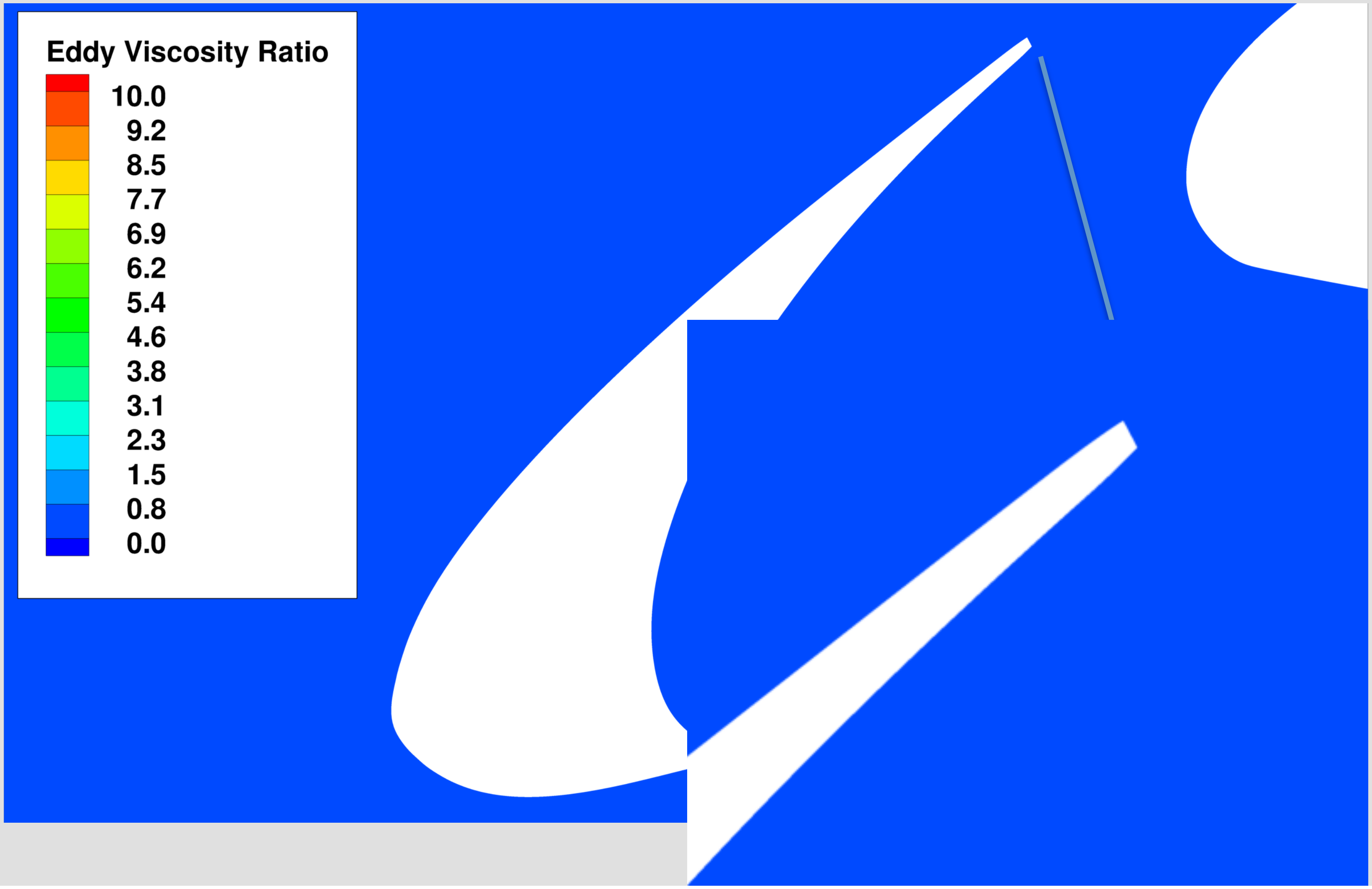
- Grid 2



- Grid 1



- Grid 2 – very low eddy viscosity ratio
- On-going results indicate similar issues on accuracy



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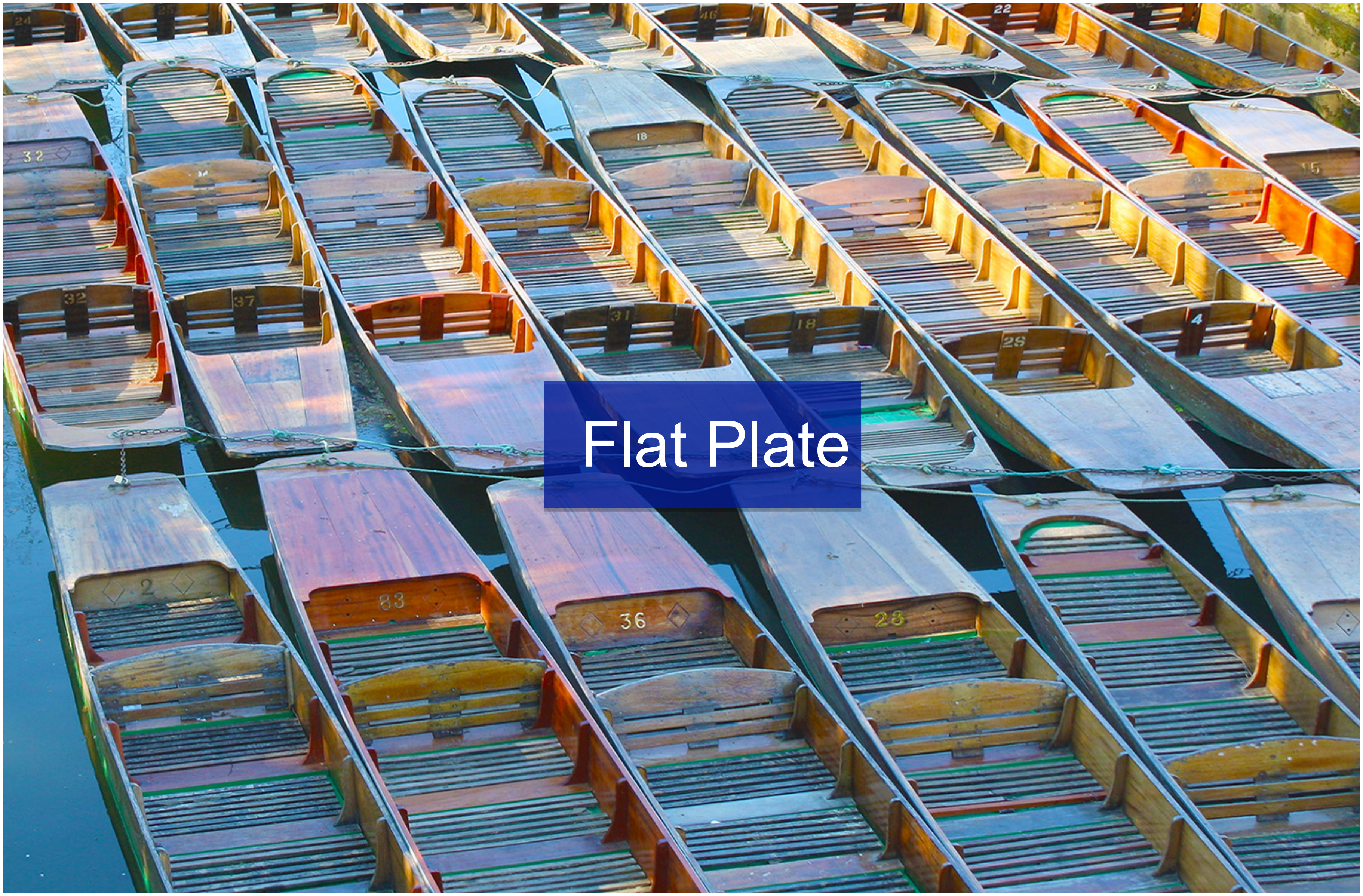


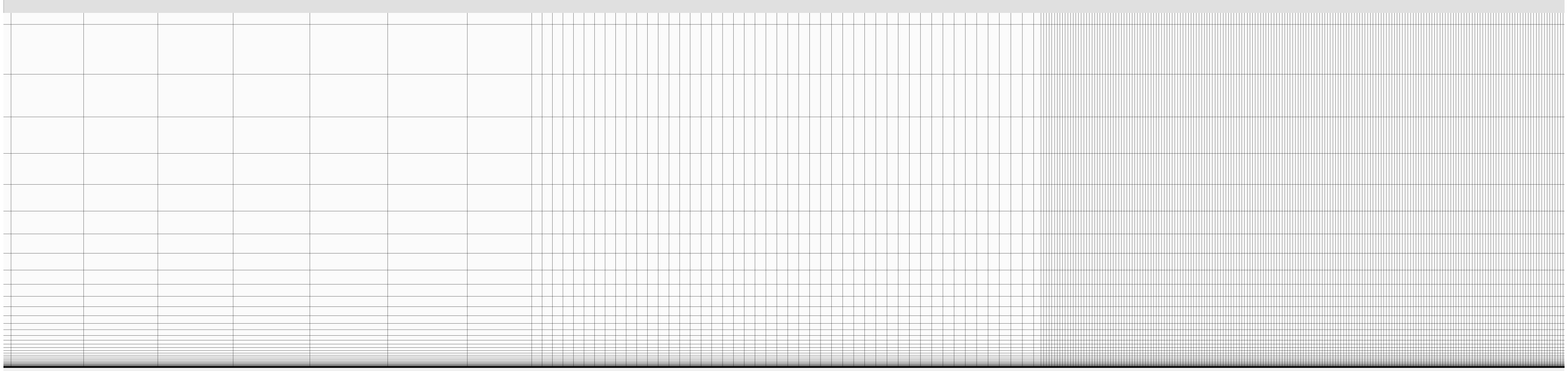
Flat Plate

Shielding

- Simple flat plate case to investigate shielding
- Re=5 million (L=1m)
- STAR-CCM+ & OpenFOAM

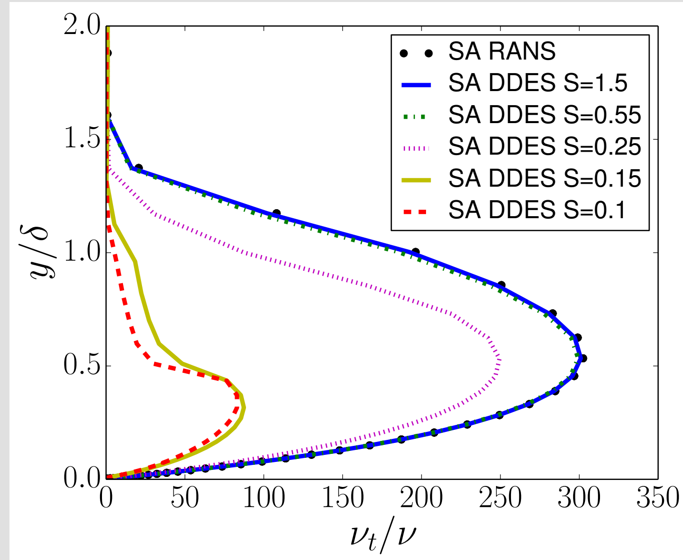
Mesh	Nx	Ny	Nz	x^+	y^+	z^+	S
Mesh 1	200	50	25	4300	0.9	89	1.5
Mesh 2	400	50	25	1599	0.9	89	0.55
Mesh 3	800	50	25	628	0.9	89	0.25
Mesh 4	1600	50	25	181	0.9	89	0.15
Mesh 5	2000	50	25	121	0.9	89	0.1

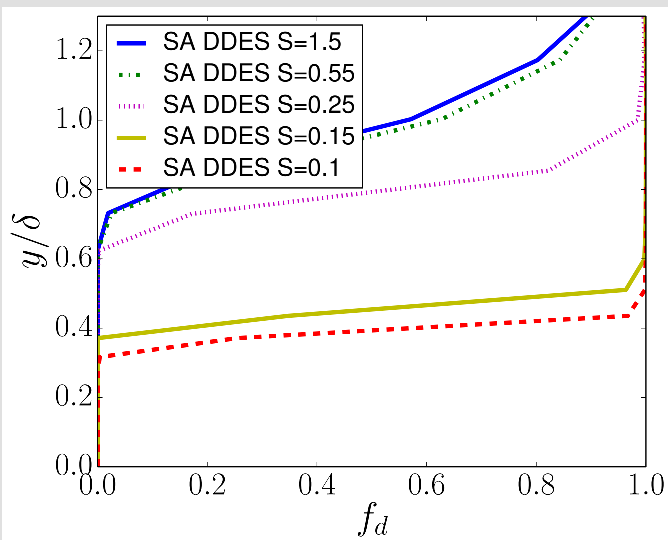
Coarse Medium Fine

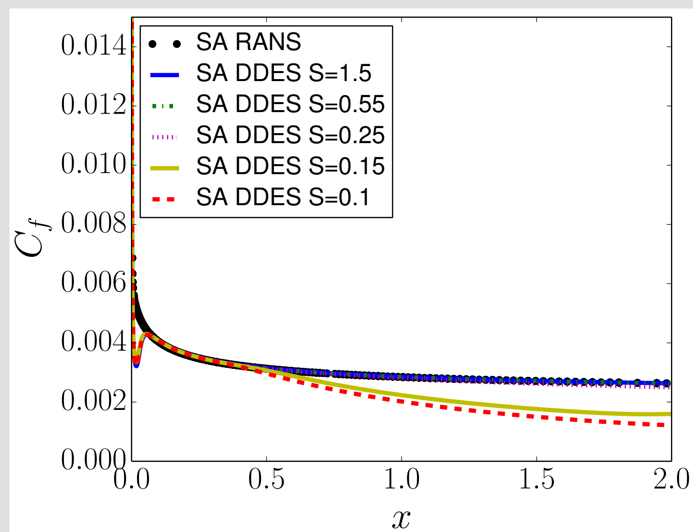


Shielding

- Once the filter-width becomes too small, the f_d function breaks down, nu_t drops and the skin-friction drops
- Non-linear feedback between DES and shielding function

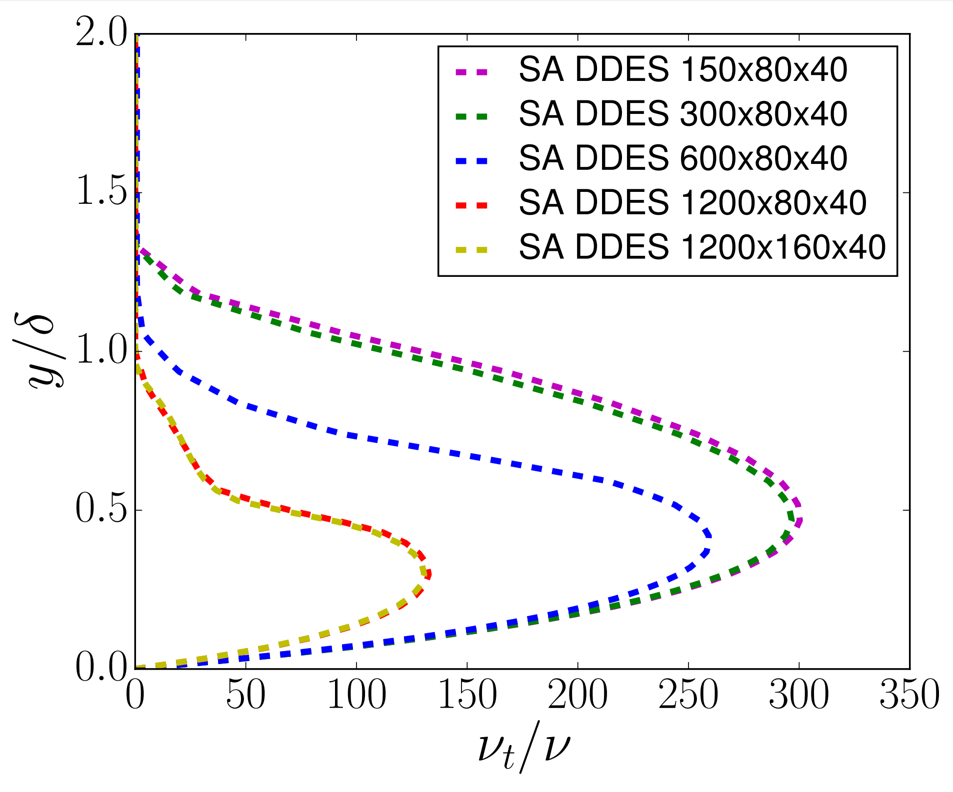






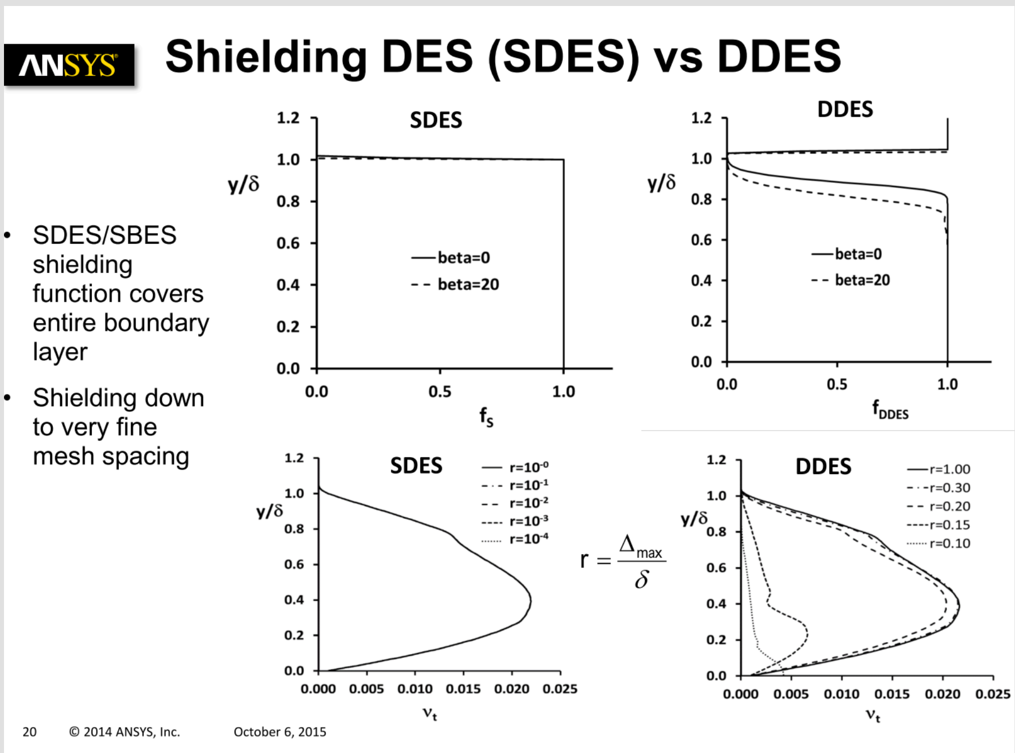
OpenFOAM

- Different grid, different numerics, different model implementation but same trend



Solution?

- Not a product placement for ANSYS! But..



- No details published of their solution
- Motivation to pursue an open-source solution

Solution?

- Not a simple solution – Changing of coefficients in the r_f/f_d isn't strong enough.
- This has been found for the SA & SST based DDES & IDDES models
- Solution therefore needs to suitable for generic DES variants.
- Main research focus – hope to provide a solution soon!

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Conclusions

Careful use of IDDES on a 2nd order unstructured solver can give very good results

Sensitivity of IDDES/DDES to the near-wall mesh resolution

Need a more robust shielding function for complex industrial grids that mix between near-wall resolutions

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Thank you

Dr Neil Ashton
neil.ashton@oerc.ox.ac.uk