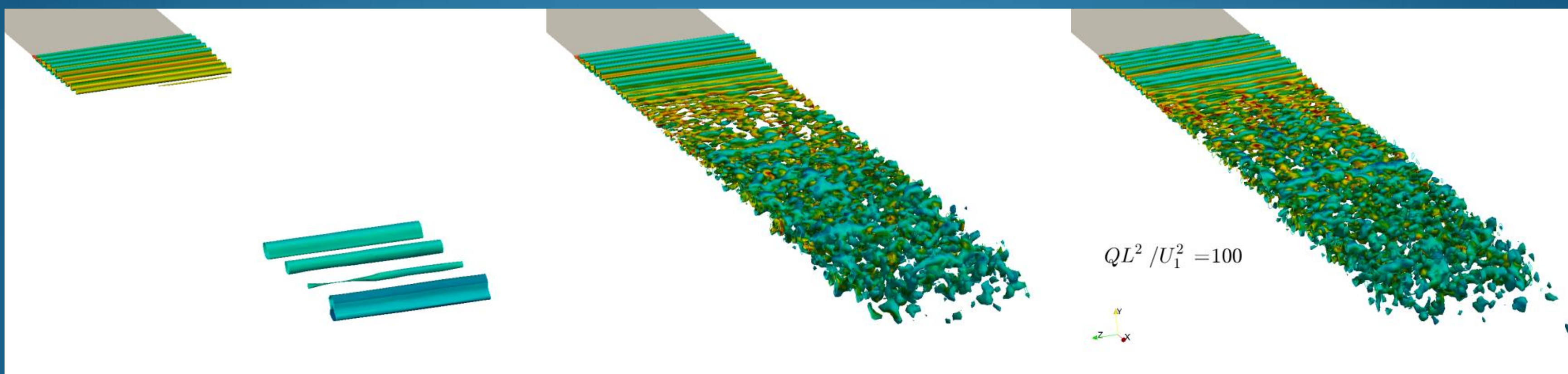
Progress in Go4Hybrid since KoM at CFDB



M. Fuchs, C. Mockett, F. Thiele

CFD Software E+F GmbH

CFD Software Entwicklungs-
und Forschungsgesellschaft mbH

Method development since KoM

Approaches applied

- Development of DDES that switches to WALE and σ models of Nicoud et al. in LES mode
  - WALE: Responds to vortices, not to plane shear
  - σ: Responds to 3D structures, not 2D/2C flow states
- We have applied this modification alone as well as in combination with the $\tilde{\Delta}_{\omega}$ adaptive length scale definition formulated by NTS

- Significant reduction of eddy viscosity in initial shear layer
- Maintains non-zonal and local formulation
  - Hence “generally-applicable method”

σ and WALE-DDES

- Coupling WALE and σ models with (D)DES:
  - We keep the (D)DES length scale unchanged
  - The velocity gradient invariant of the underlying RANS model, $S^*{}_{RANS}$ is substituted with the WALE or σ formulation in LES mode regions only
    - For S-A based DES, $S^*{}_{RANS} = \sqrt{2\Omega_{ij}\Omega_{ij}}$
- Blending function for DDES:

$$S^*_{(W,\sigma)-DDES} = S^*_{RANS} - f_d \, \mathrm{pos}(L_{RANS} - L_{LES}) \, (S^*_{RANS} - B_{W,\sigma} \, S^*_{W,\sigma})$$

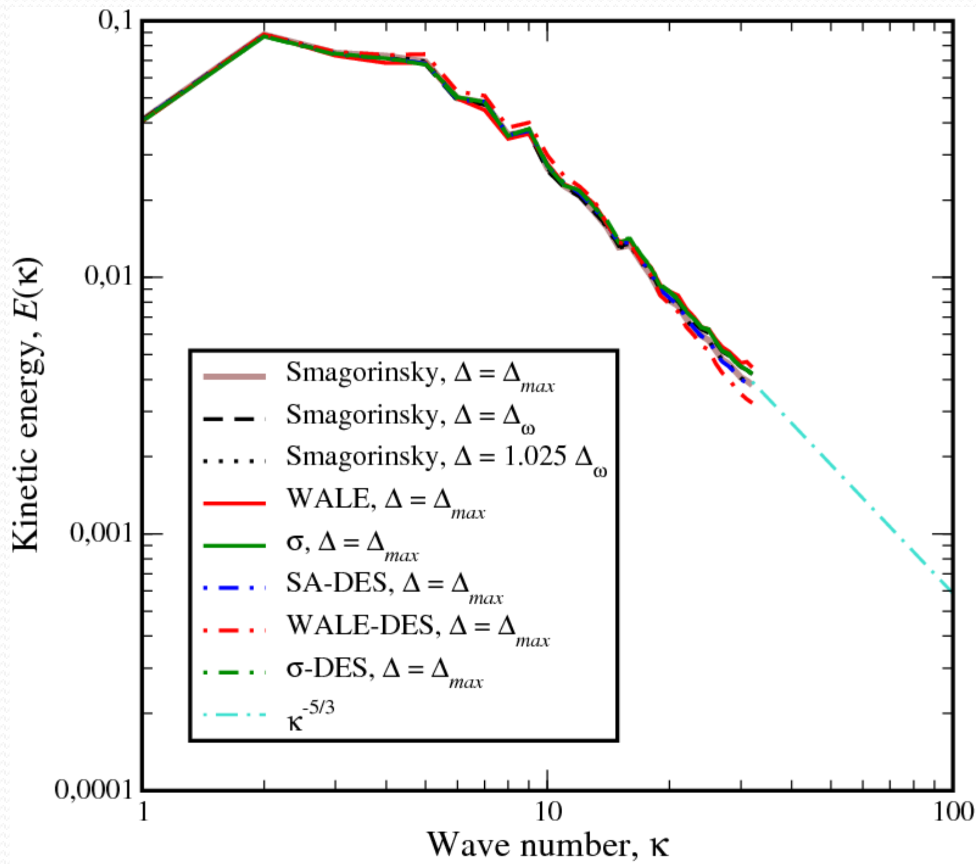
$$\mathrm{pos}(a) = \begin{cases} 0 & , \text{if } a \leq 0 \\ 1 & , \text{if } a > 0 \end{cases}$$

- Coefficient *B* gives same value of C_{DES} irrespective of WALE/σ modification

$$B_{W,\sigma} = C^2_{W,\sigma} / C^2_S$$

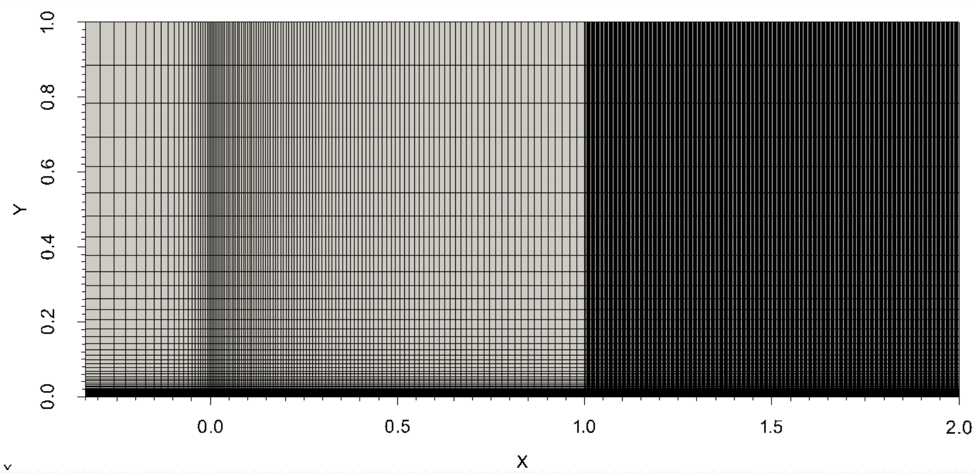
Basic tests

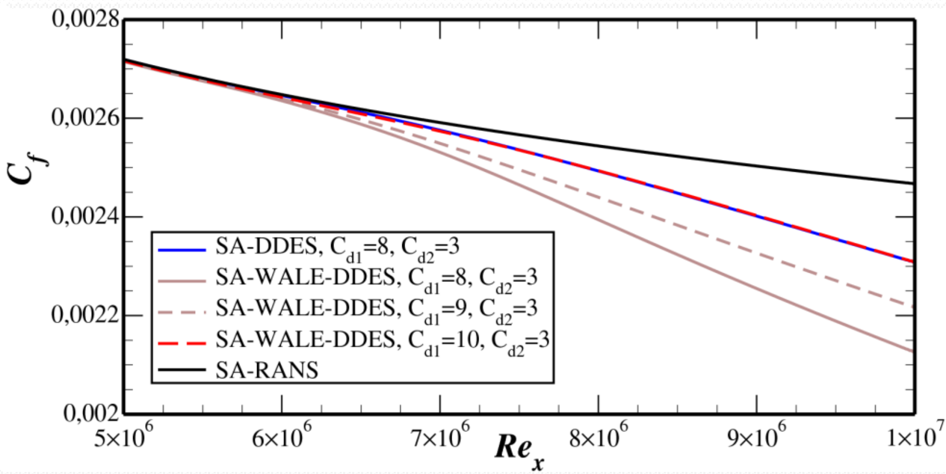
- Decaying isotropic turbulence used to show for “fully-developed” turbulence:
  - That standard DES, WALE-DES and σ-DES all give equivalent behaviour
    - With calibrated values of model constants
  - That $\tilde{\Delta}_\omega$ gives equivalent behaviour to Δ_{max}



Basic tests

- Flat plate boundary layer with "ambiguous" grid used to test WALE-DDES and σ-DDES shield functions
- Recalibration from $C_{d1} = 8$ to $C_{d1} = 10$ needed to give equivalent functionality to SA-DDES

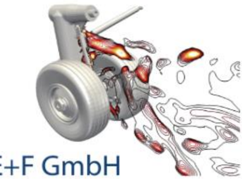




Initial results: Spatial shear layer test case

F2 – test case setup

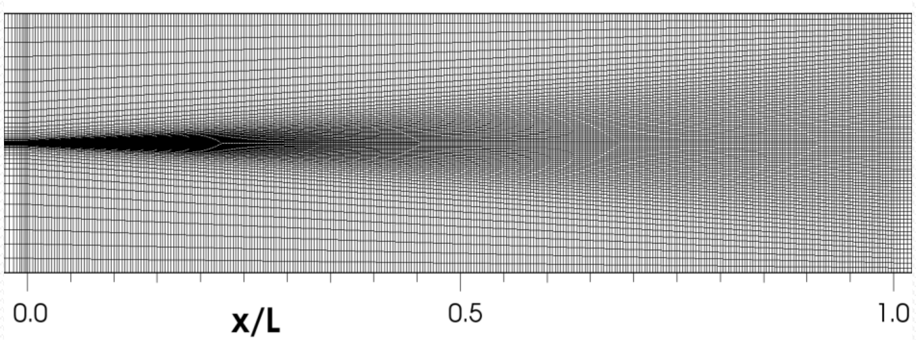
- Pressure-based incompressible solver
- Turbulence modelling approach: non-zonal delayed DES
- Numerical convection scheme: 2nd order central differences
- Time step size:
  - Coarse grid: $\Delta t = 4 \times 10^{-5}$
  - Fine grid: $\Delta t = 2 \times 10^{-5}$
- Averaging time for statistics:
  - t_{avg} = 0.8 – 1.37 s = 25.7 – 44 CTU
    (1 CTU based on U_M = 32.1 m/s and L = 1 m)



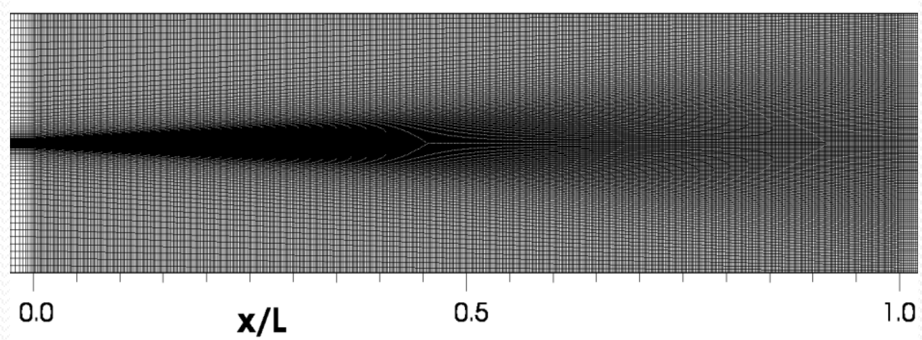
F2 – test case setup

- 2 grids used so far:
  - Fine grid (small domain) as provided by J. Kok (NLR)
  - Coarse grid (every 2nd grid point in each direction)

  → except for x-resolution on plate to maintain equivalent velocity profiles at leading edge



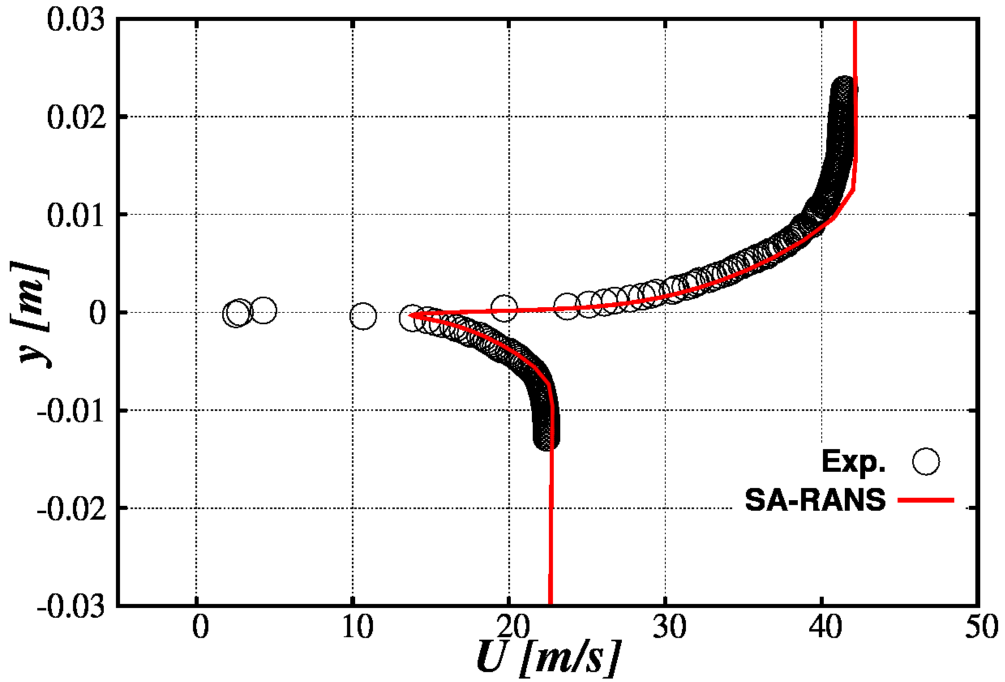
coarse grid (small domain) – 1.4 x 10^6 cells



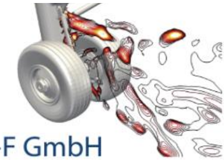
fine grid (small domain) – 10.3 x 10^6 cells

F2 – test case setup

- Spalart-Allmaras as RANS background model for all simulations
- Length of BL section and transition location taken from paper of S. Deck:
  - Upper leading edge - 0.82m, transition at -0.708m
  - Lower leading edge - 0.46m, transition at -0.388m



Small domain seems to be OK for incompressible OpenFOAM® solver



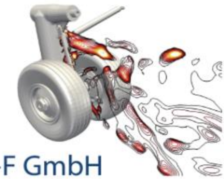
F2 - conducted simulations

coarse grid

	SA-DDES	SA-WALE-DDES	SA-σ-DDES
Δ_{max}	X	X	X
$\widetilde{\Delta}_{\omega}$	X	X	X

fine grid

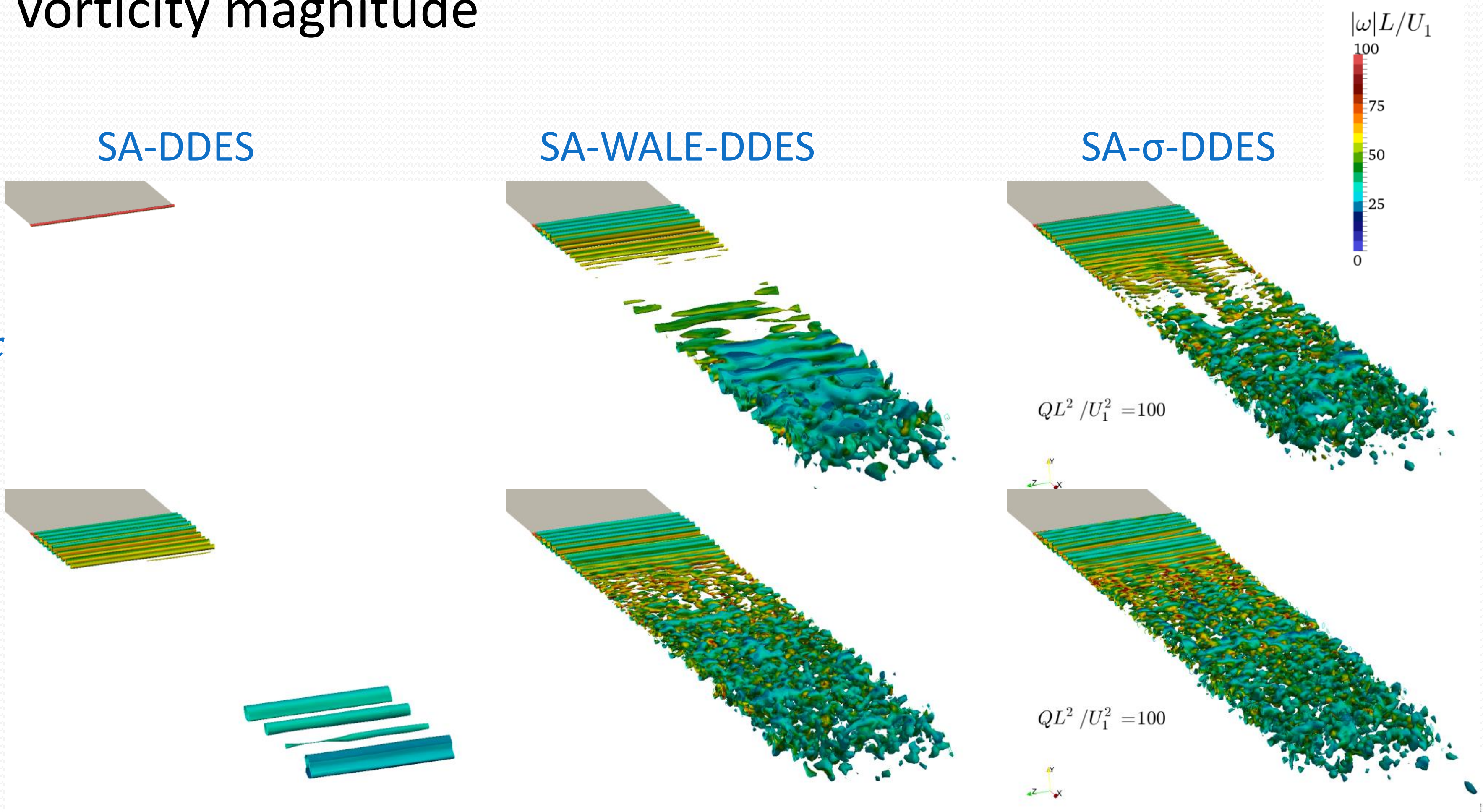
	SA-DDES	SA-WALE-DDES	SA-σ-DDES
Δ_{max}			
$\widetilde{\Delta}_{\omega}$		X	X



CFD Software E+F GmbH

F2 - results

- Turbulent structures visualised via Q criterion shaded by vorticity magnitude



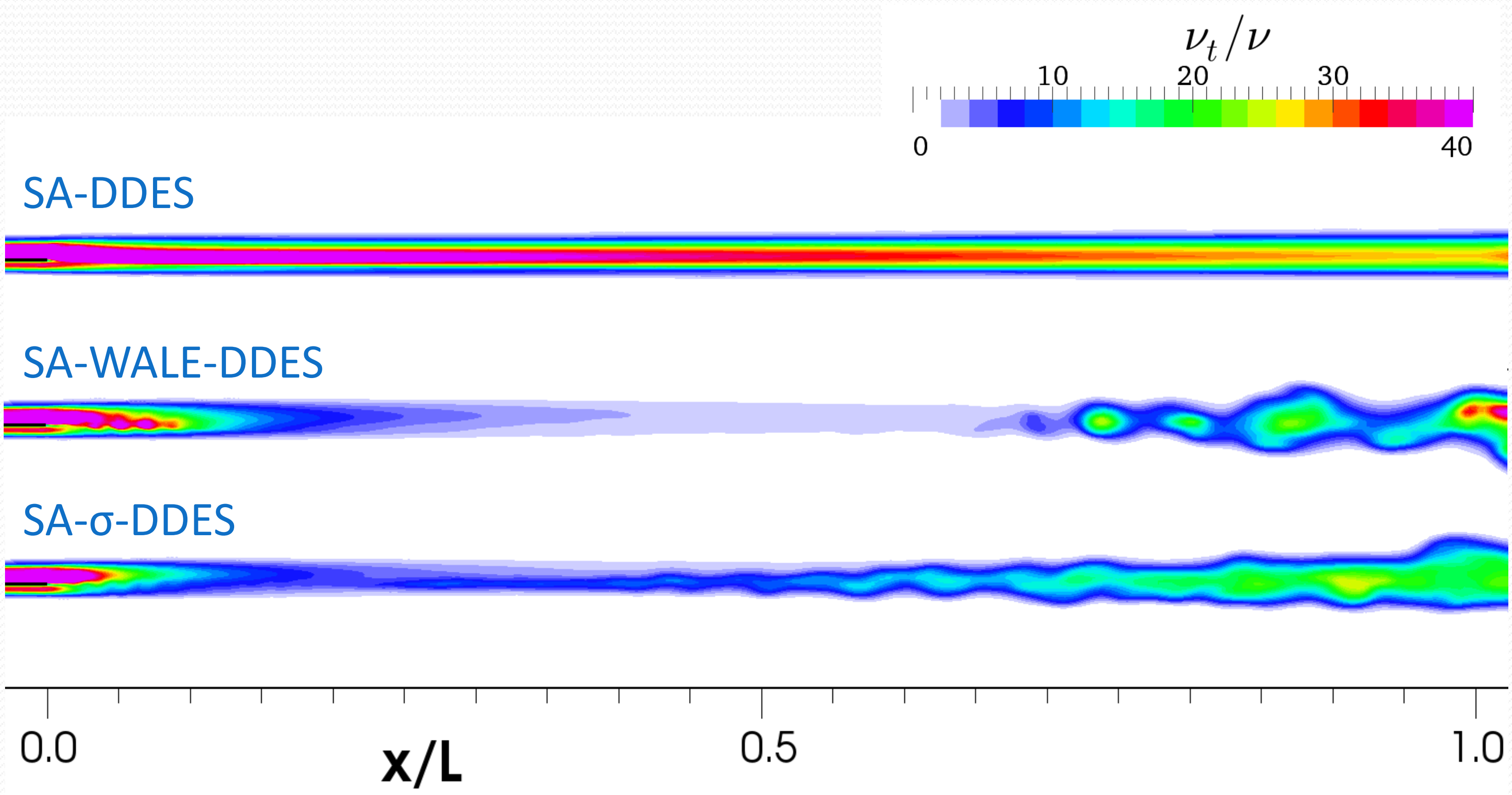
Δ_{max}

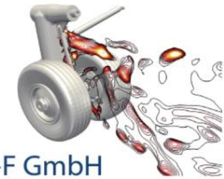
$\tilde{\Delta}_{\omega}$

F2 - results

Go4Hybrid

- DDES variants with Δ_{max}:

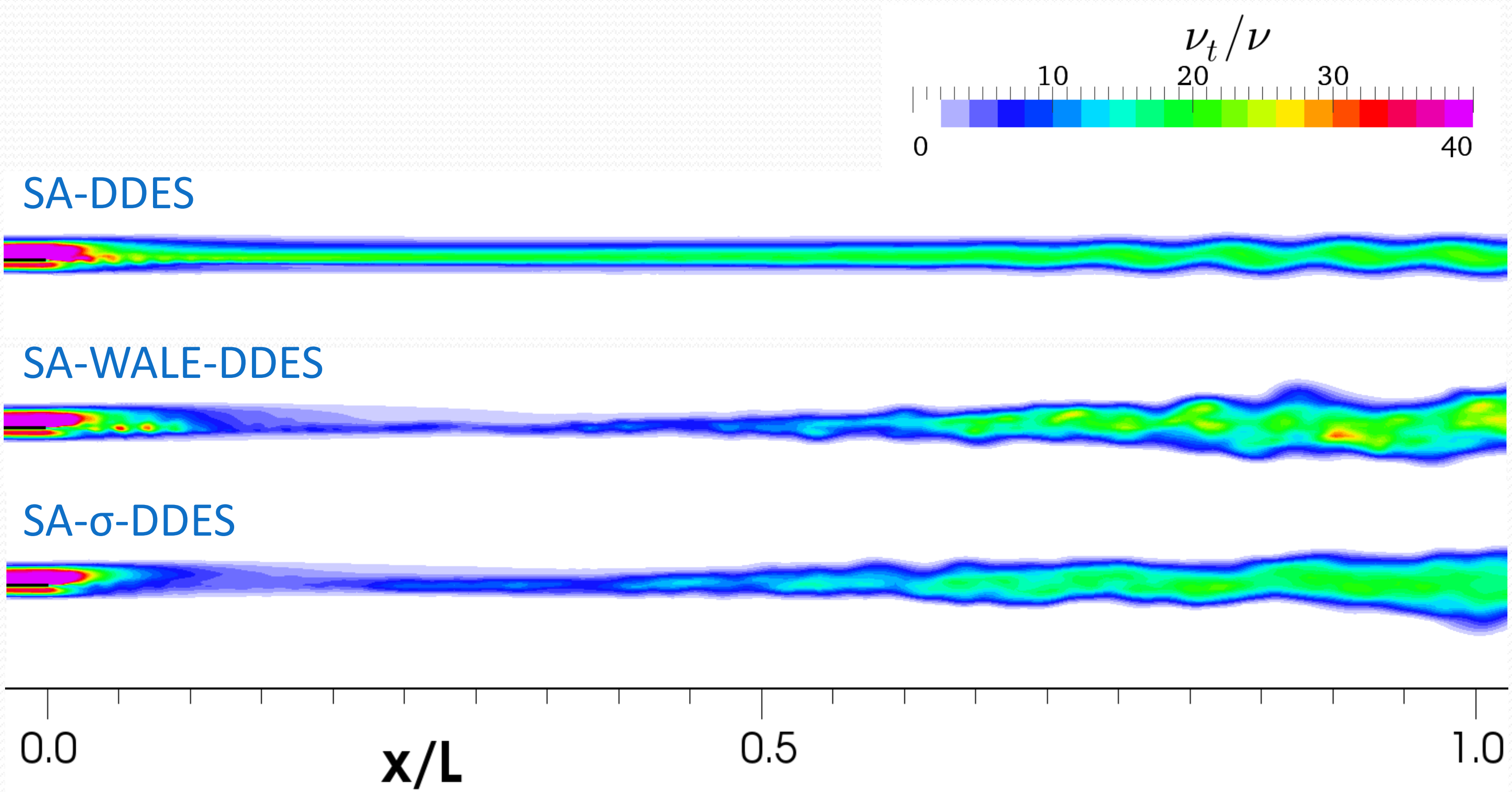




CFD Software E+F GmbH

F2 - results

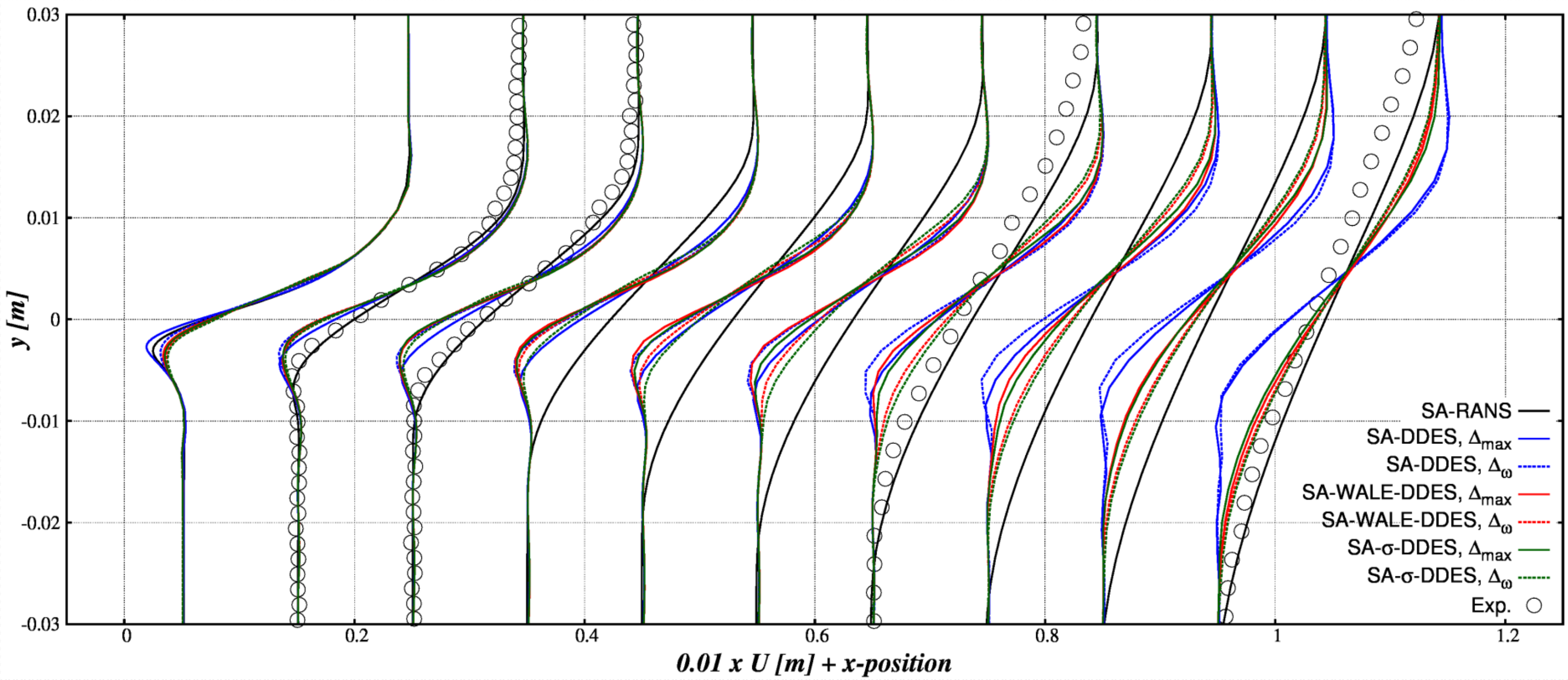
- DDES variants with $\tilde{\Delta}_{\omega}$:

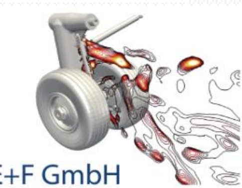


F2 - results

- Streamwise velocity component:

coarse grid



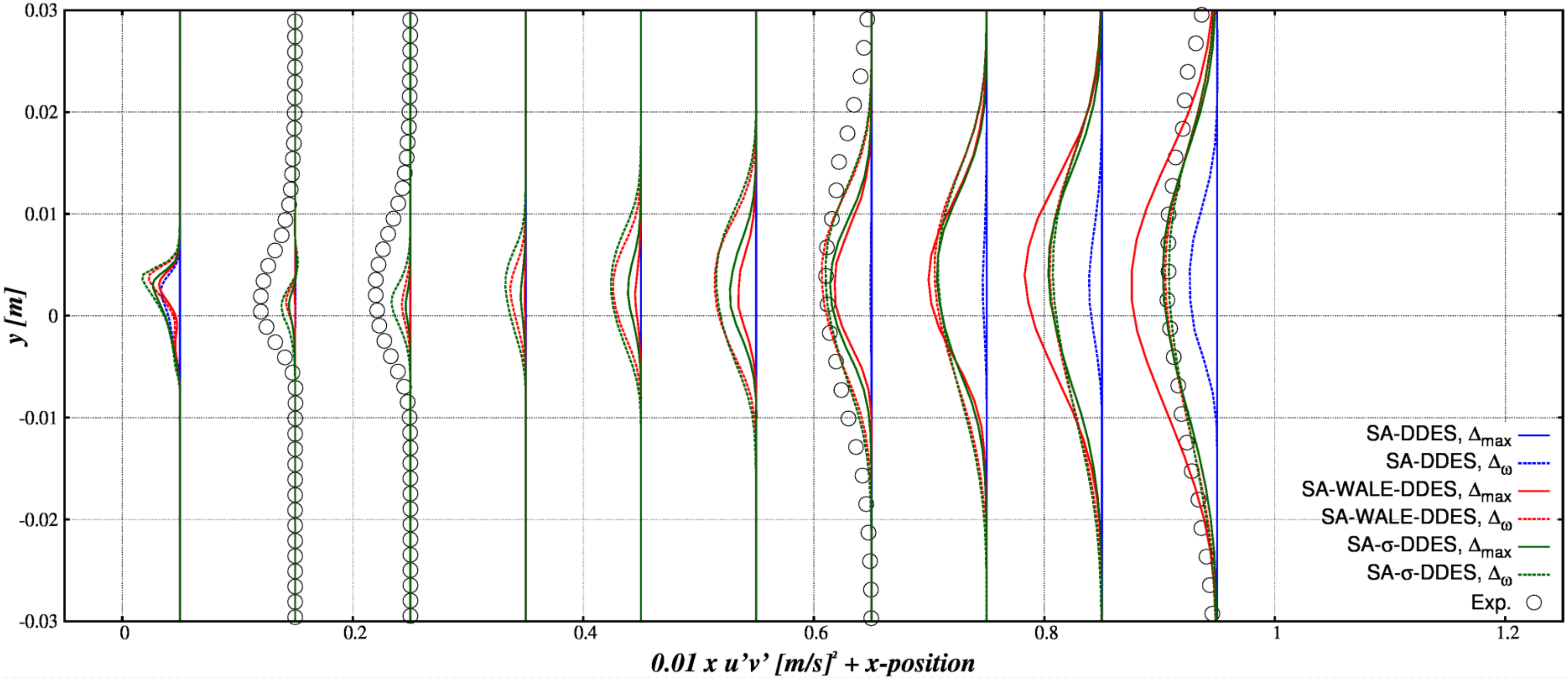


CFD Software E+F GmbH

F2 - results

- Resolved Reynolds stress component u'v':

coarse grid

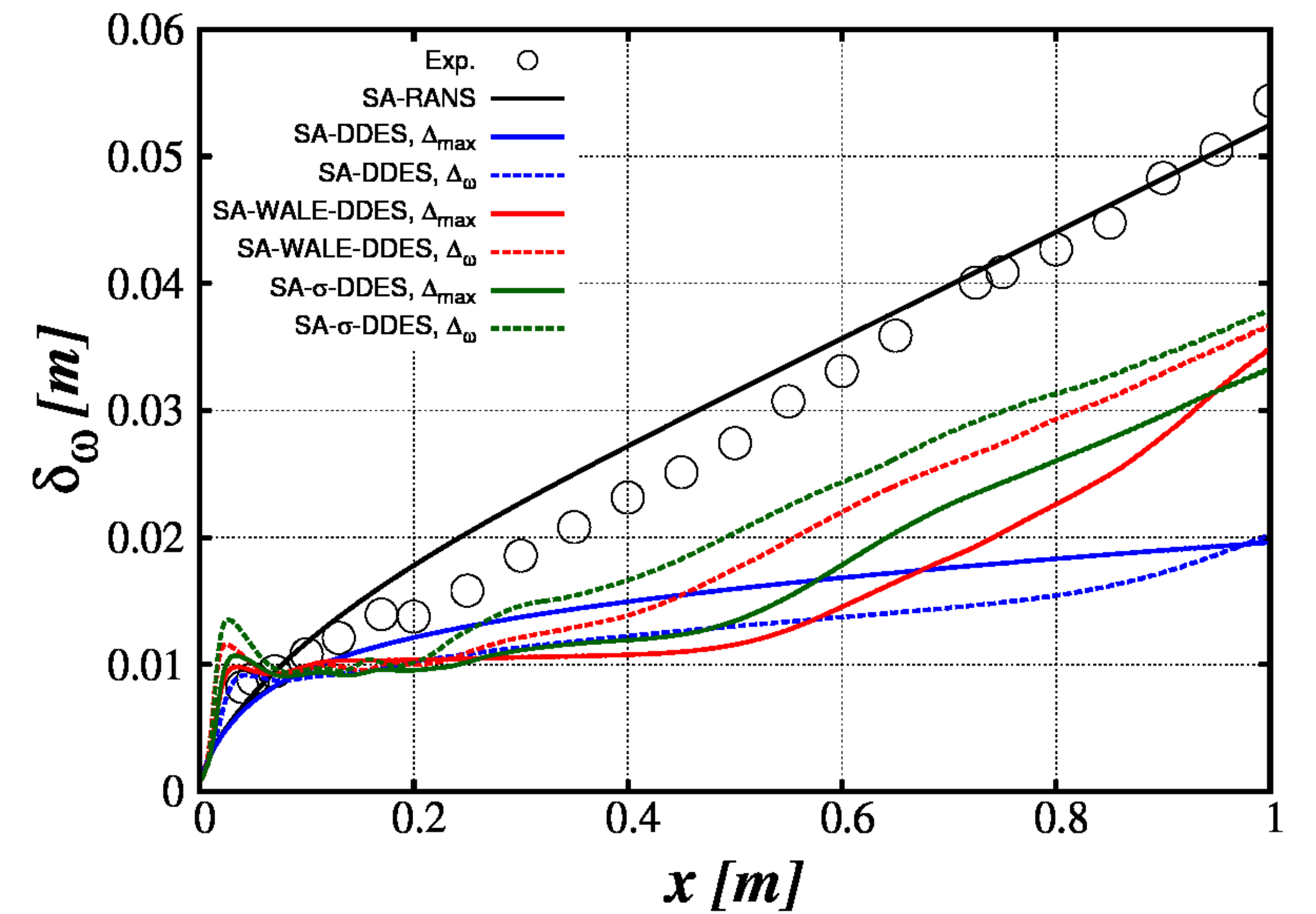


CFD Software E+F GmbH

F2 - results

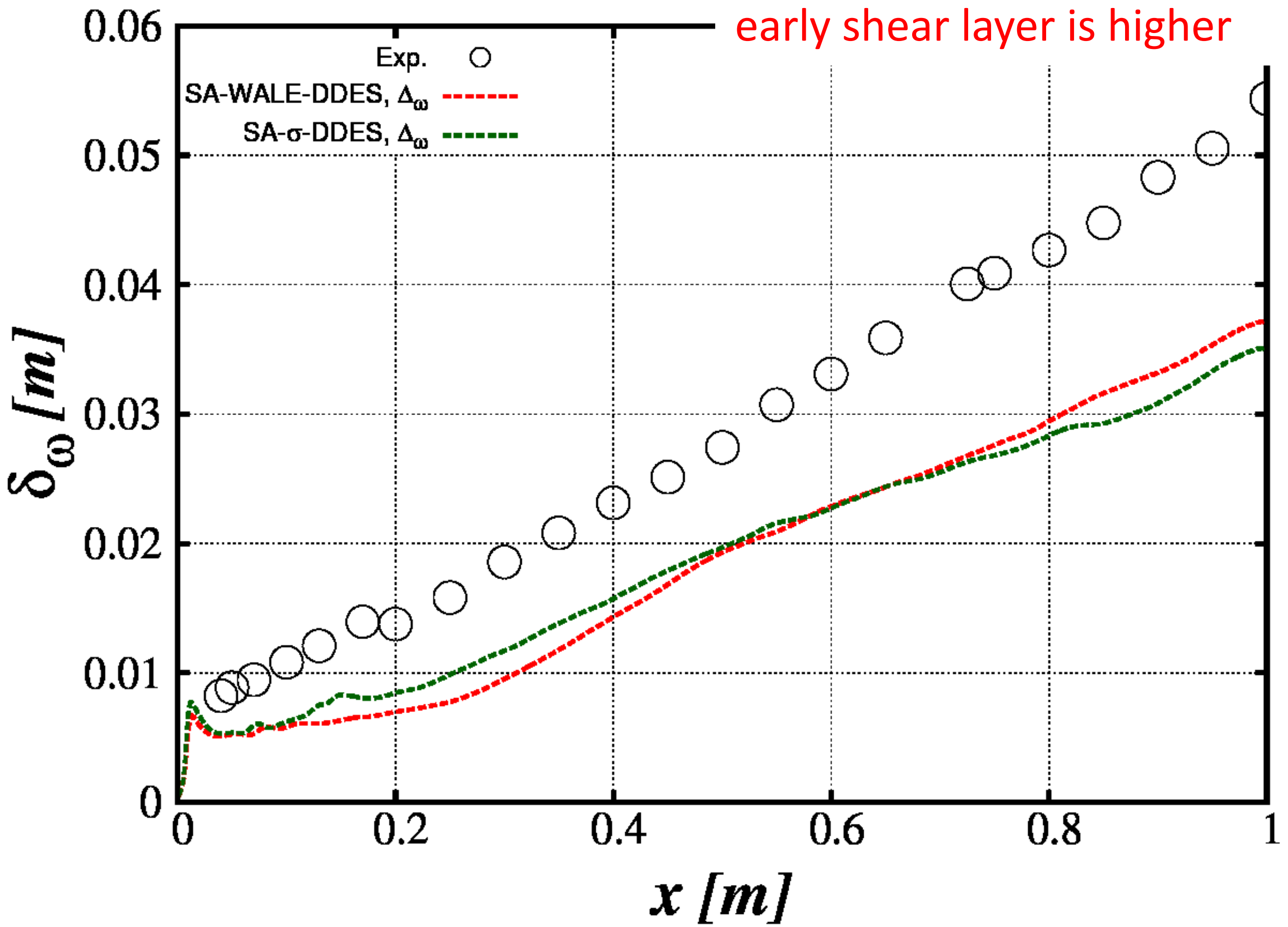
Go4Hybrid

coarse grid



F2 - results

fine grid



results do <u>not</u> improve with grid refinement so far ☹

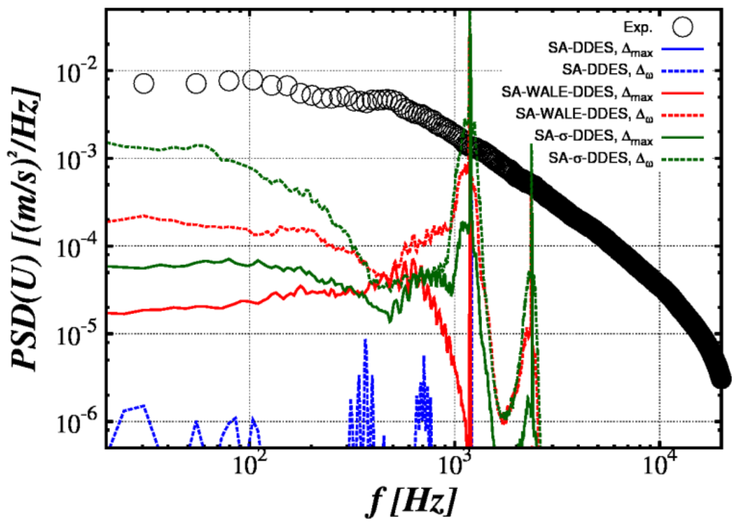
→ Penalty of reduced eddy viscosity in early shear layer is higher

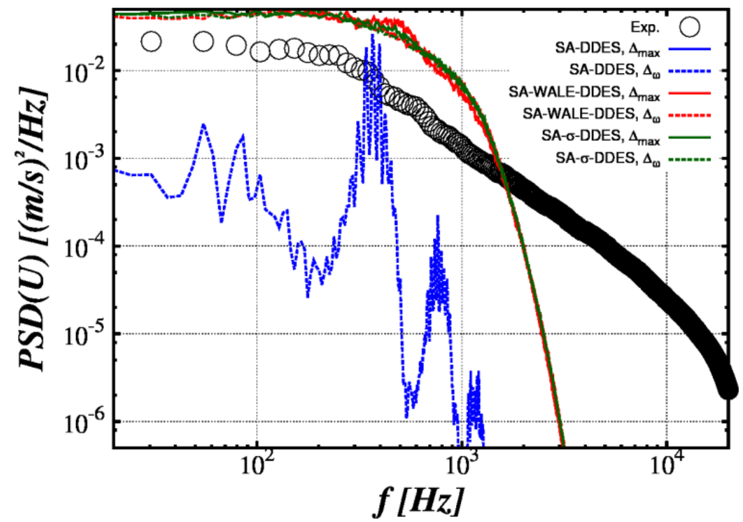
F2 - results

Go4Hybrid

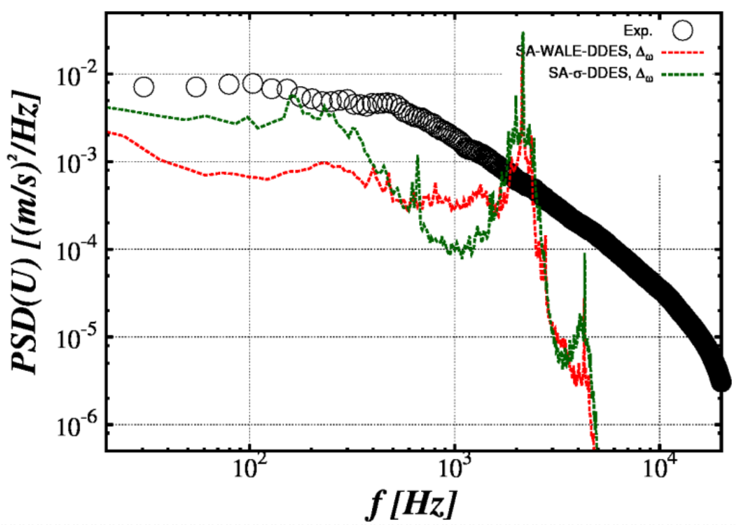
x = 0.2m | x = 0.8m

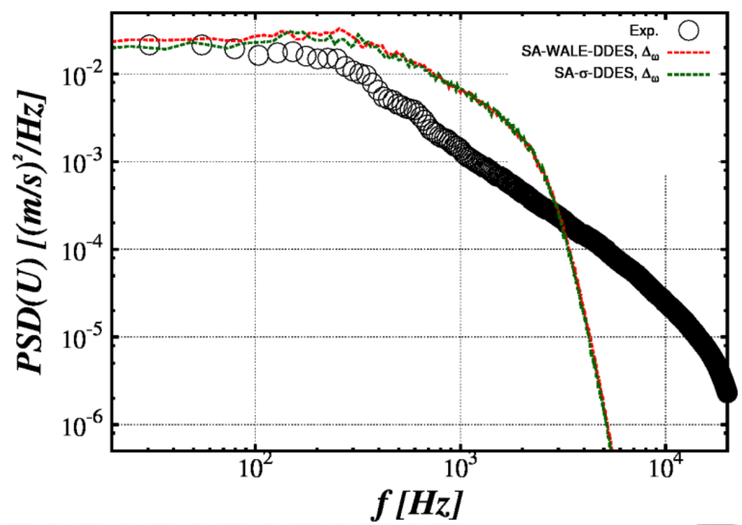
coarse grid

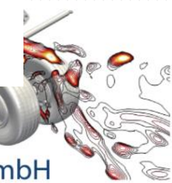




fine grid







CFD Software E+F GmbH

Next steps

- Assessment of new methods for “natural” DES application:
  - e.g. NACA0021
- Go4Hybrid test cases until next meeting in October:
  - Jet
  - Delta Wing
- Test σ/WALE-DDES for WMLES of channel flow

Thank you for your attention

Extra slides

$\widetilde{\Delta}_{\omega}$ - approach of NTS

- The maximum cell length is normally used in DES
  - $\Delta_{max} = \max(\Delta_x, \Delta_y, \Delta_z)$
- Typically, shear layers are resolved more coarsely in the spanwise, *z* direction
  - i.e. $\Delta_z \gg \Delta_x, \Delta_y$
- The early shear layer is characterised by 2D structures in the *x,y* plane
- It seems justified to reduce to $\max(\Delta_x, \Delta_y)$ in such situations
- Dominance of Δ_z in Δ_{max} contributes to excessive eddy viscosity in early shear layer

$\tilde{\Delta}_\omega$ - approach of NTS

Go4Hybrid

- Similar principle to adaptive formulation of Chauvet et al. (2011), Δ_ω
  - Sensitised to the orientation of vorticity vector with grid
- However, in "2D flow regions", their formulation reduces to $\sqrt{\Delta_x \Delta_y}$
  - Undesirable in the same way as the cube root formulation, since the smallest dimension has too much influence
- We propose an alternative:

$$\tilde{\Delta}_\omega = \frac{1}{\sqrt{3}} \max_{n,m=1,8} |(\mathbf{l}_n - \mathbf{l}_m)|$$

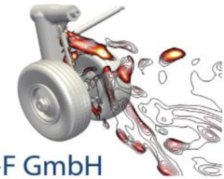
  - where $\mathbf{l}_n = \mathbf{n}_\omega \times (\mathbf{r}_n - \mathbf{r})$, $\mathbf{r}$ is the cell centre, $\mathbf{r}_n$ are cell vertices and $\mathbf{n}_\omega$ is the unit vector aligned with the vorticity vector.
- This gives $O(\max\{\Delta_x, \Delta_y\})$ in "2D flow regions"

Alternative SGS models in LES mode

$$\nu_{sgs} = (C_{sgs}\Delta)^2\, \mathscr{D}_{sgs}(u) \qquad B_{W,\sigma} = C_{W,\sigma}^2 / C_S^2$$

Model	C_{sgs}	$\mathscr{D}_{sgs}(u)$
Smagorinsky [10]	C_S	$\sqrt{2S_{ij}S_{ij}}$
WALE [7]	C_W	S_W^*
σ [8]	C_σ	S_σ^*
DES [13, 12]	$\sqrt{A}\, C_{DES}\, \Psi$	S_{RANS}^*
WALE-DES	$\sqrt{A}\, C_{DES}\, \Psi$	$B_W\, S_W^*$
σ-DES	$\sqrt{A}\, C_{DES}\, \Psi$	$B_\sigma\, S_\sigma^*$

Parameter	Calibrated value
C_S	0.20
C_W	0.58
C_σ	1.68
C_{DES} (for SA-DES)	0.65
B_W	8.08
B_σ	67.8



WALE and σ models

Model	Smagorinsky (Ref. 1)	WALE (Ref. 5)	Vreman (Ref. 6)	σ-model
Operator	$\sqrt{2S_{ij}S_{ij}}$	Eq. (4)	Eq. (5)	Eq. (20)
Model constant	$C_s \approx 0.165$	$C_w \approx 0.50$	$C_v \approx 0.28$	$C_\sigma \approx 1.35$
P0	Yes	Yes	Yes	Yes
Asymptotic	$O(y^0)$	$O(y^3)$	$O(y)$	$O(y^3)$
P1	No	Yes	No	Yes
Solid rotation	0	~0.90	~0.71	0
Pure shear	1	0	0	0
P2	No	No	No	Yes
Axisymmetric	~3.46	~0.15	~1.22	0
Isotropic	~2.45	0	1	0
P3	No	No	No	Yes

WALE model:

$$\mathcal{D}_w = \frac{(\mathcal{S}^d_{ij}\mathcal{S}^d_{ij})^{3/2}}{(S_{ij}S_{ij})^{5/2} + (\mathcal{S}^d_{ij}\mathcal{S}^d_{ij})^{5/4}}$$

$$\mathcal{S}^d_{ij} = \frac{1}{2}(g^2_{ij} + g^2_{ji}) - \frac{1}{3}g^2_{kk}\delta_{ij}, \quad \text{with} \quad g^2_{ij} = g_{ik}g_{kj}.$$

σ model:

$$\mathcal{D}_\sigma = \frac{\sigma_3(\sigma_1 - \sigma_2)(\sigma_2 - \sigma_3)}{\sigma_1^2}$$

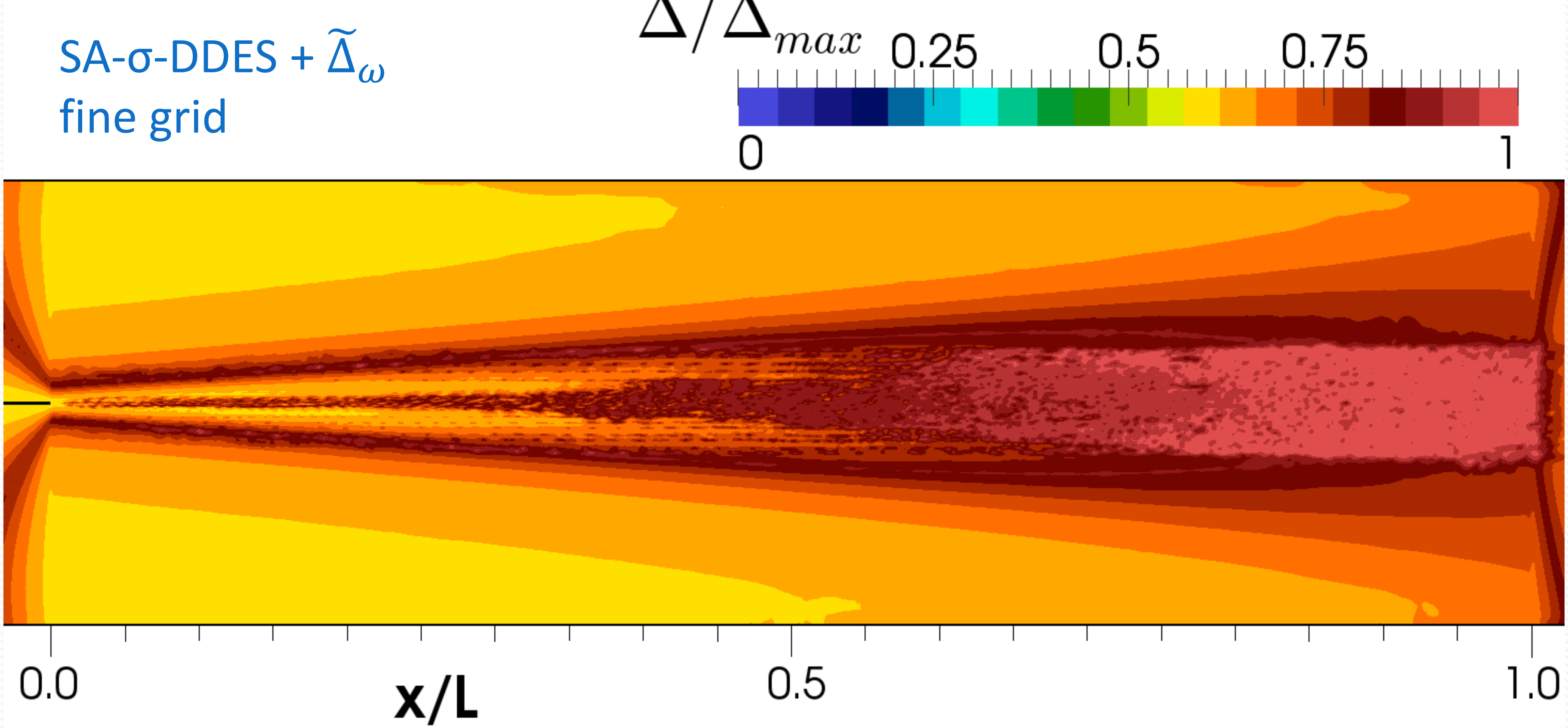
$\sigma_1 \geq \sigma_2 \geq \sigma_3 \geq 0$, the three singular values of the velocity gradient tensor $\mathbf{g} = (g_{ij})$.

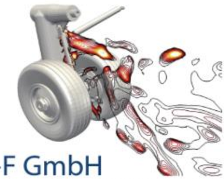
F2 – flow solver used by CFDB

- Customised version of OpenFOAM®
  - Open source software
  - Unstructured (arbitrary polyhedral cells)
  - Cell-centred, finite volume solver
  - 2^{nd} order accurate in space and time
  - <u>Incompressible</u> solver employed here
  - SIMPLE-like pressure-velocity coupling
  - Customised features:
    - State-of-the-art, validated & calibrated DES models
    - Hybrid convection scheme of Travin et al. for DES
      - Local blending between 2^{nd} order upwind and 2^{nd} order central schemes
    - Improved transient solver

F2 - results

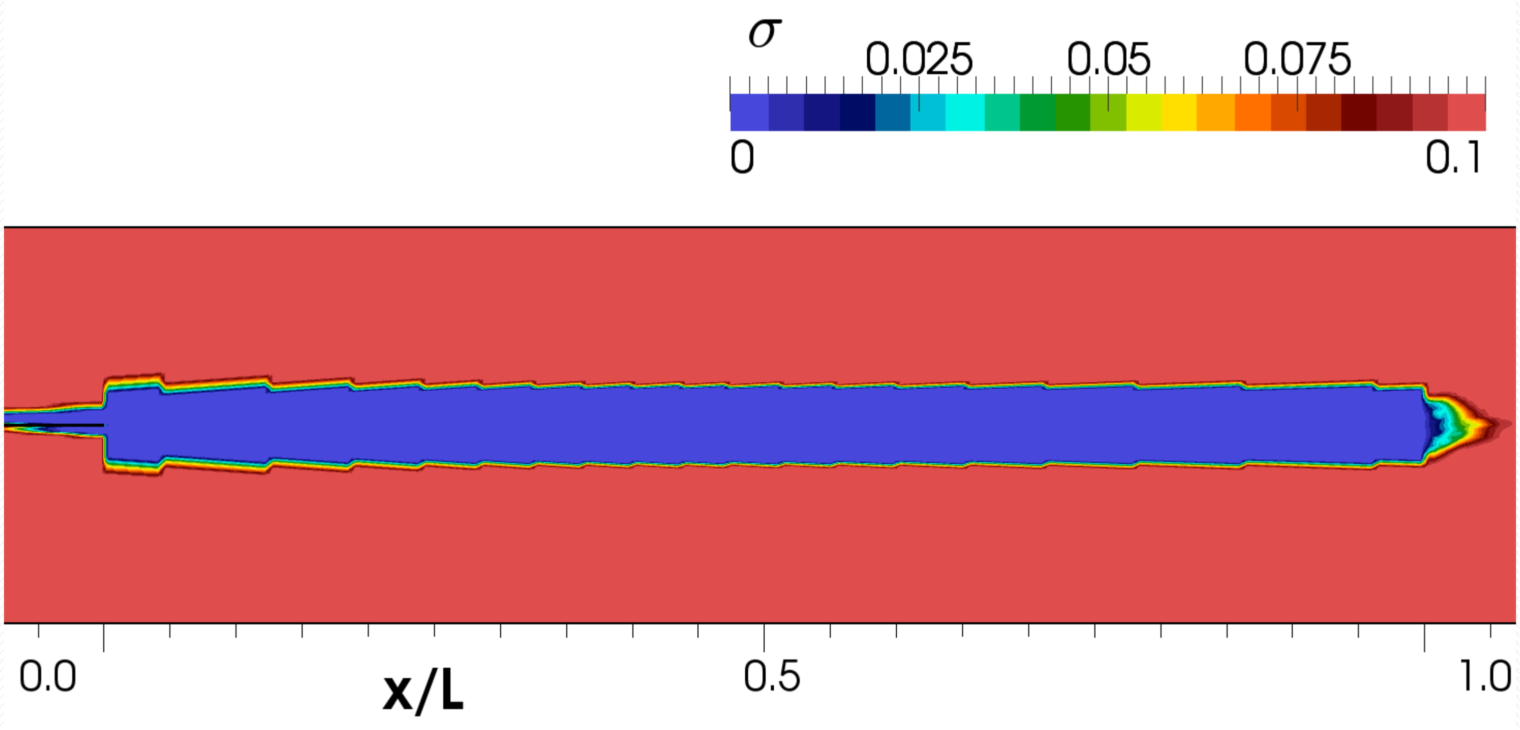
SA-σ-DDES + $\widetilde{\Delta}_\omega$
fine grid





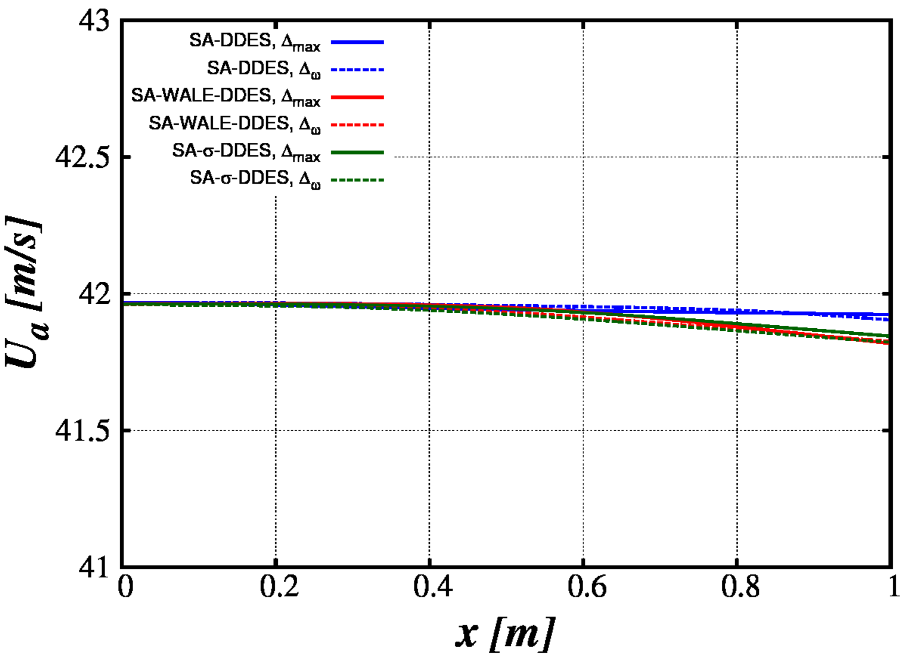
F2 - numerics

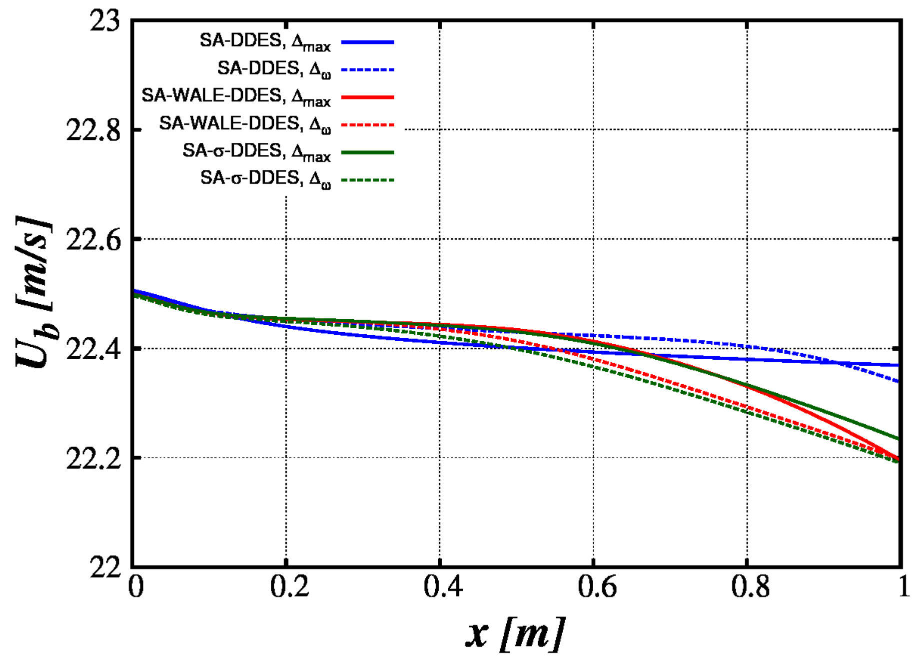
- 2nd order central differences are assured within the shear layer focus region („box solution“):



F2 - setup

- Evolution of upper and lower „farfield“ values of reference velocities (coarse grid):





F2 - results

- Zoom ($0 < x < 0.2$m)