



Towards LES for aeronautical applications – exploration of strategies for wall- modelling, accuracy and efficiency

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Session: Aircraft and spacecraft system analysis – 2025-10-14, 13:00-15:00

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Overview



- Background and industry needs
- Formulation of the *LESisMORE* research project
- Summary of the first year of *LESisMORE* activities
- Summary and outlook

Background and industry needs

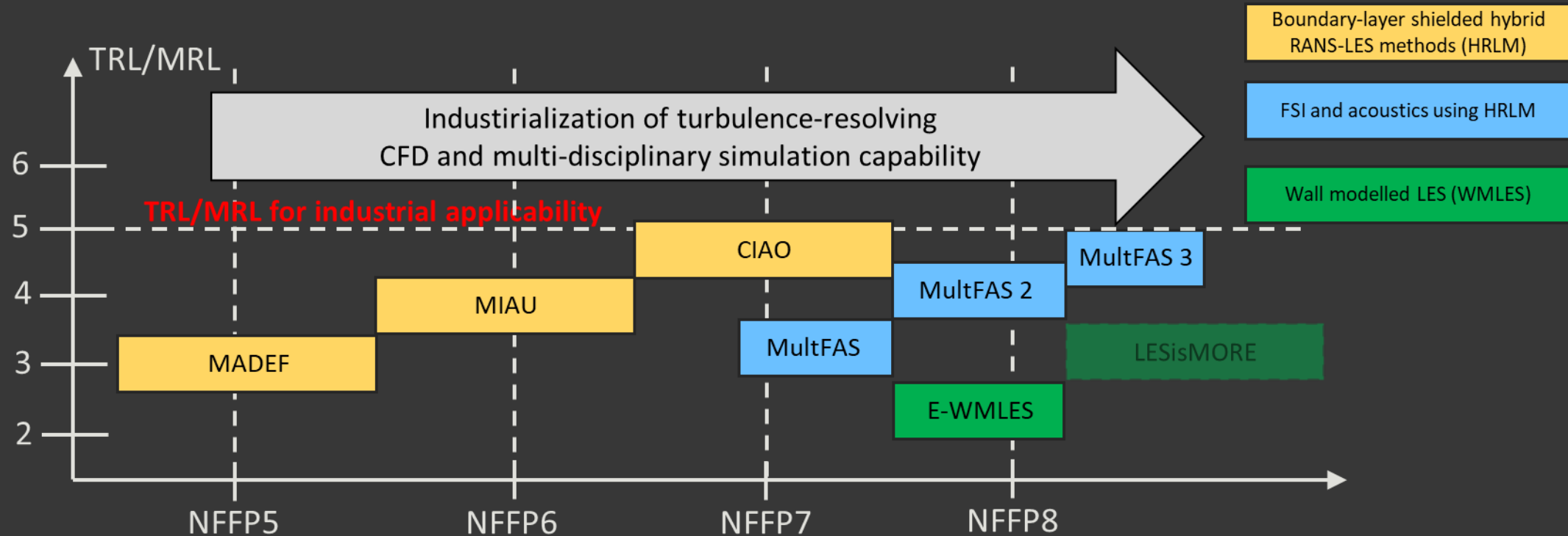
CFD for next generation aircraft design



- New and innovative aircraft configurations, military and civil, drives the need for thorough analysis and optimization
 - Need of accurate and reliable CFD methods to achieve the best possible aerodynamic design given the operational requirements
- New technologies and weight reduction strategies will require innovative design solutions where installation and interaction effects are of high importance
 - In need of a large step in accuracy and reliability with respect to modeling and simulation capabilities
- Much shorter time frames and reduced budgets requires a more digitalized and CFD based development process – the efficiency of traditional CFD solvers is challenges
 - Need for more efficient CFD solvers and alternative hardware platforms to substantially cut execution time of advanced flow simulations

➔ *Needs to go towards efficient and reliable turbulence-resolving CFD in aeronautical applications*

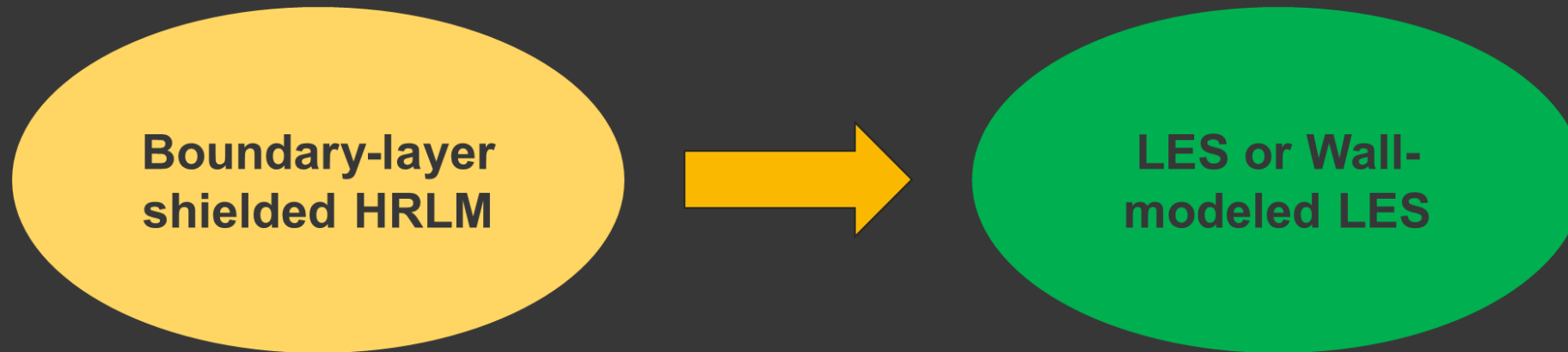
Saab's strategy of turbulence-resolving methods towards industrial applicability



Maturation of turbulence-resolving and multi-disciplinary methods towards industrial introduction using the Swedish national aviation research programme NFFP.

Treatment of boundary layers

- The NFFP7 project CIAO + industry experience have shown that boundary-layer shielded hybrid RANS-LES methods (HRLM), e.g. DDES, does not fulfil the accuracy needs and the need for turbulent statistics in e.g. intake flows → resolved boundary layer turbulence is needed



Challenge

- Smaller turbulent scales needs to be resolved → increased grid resolution and smaller time-step → increased computational cost
- RANS → LES drives the need for accurate discretization schemes to capture resolved boundary layer turbulence
- New solver approaches and modeling techniques needed to change the increasing cost per simulation

Identified key parameters

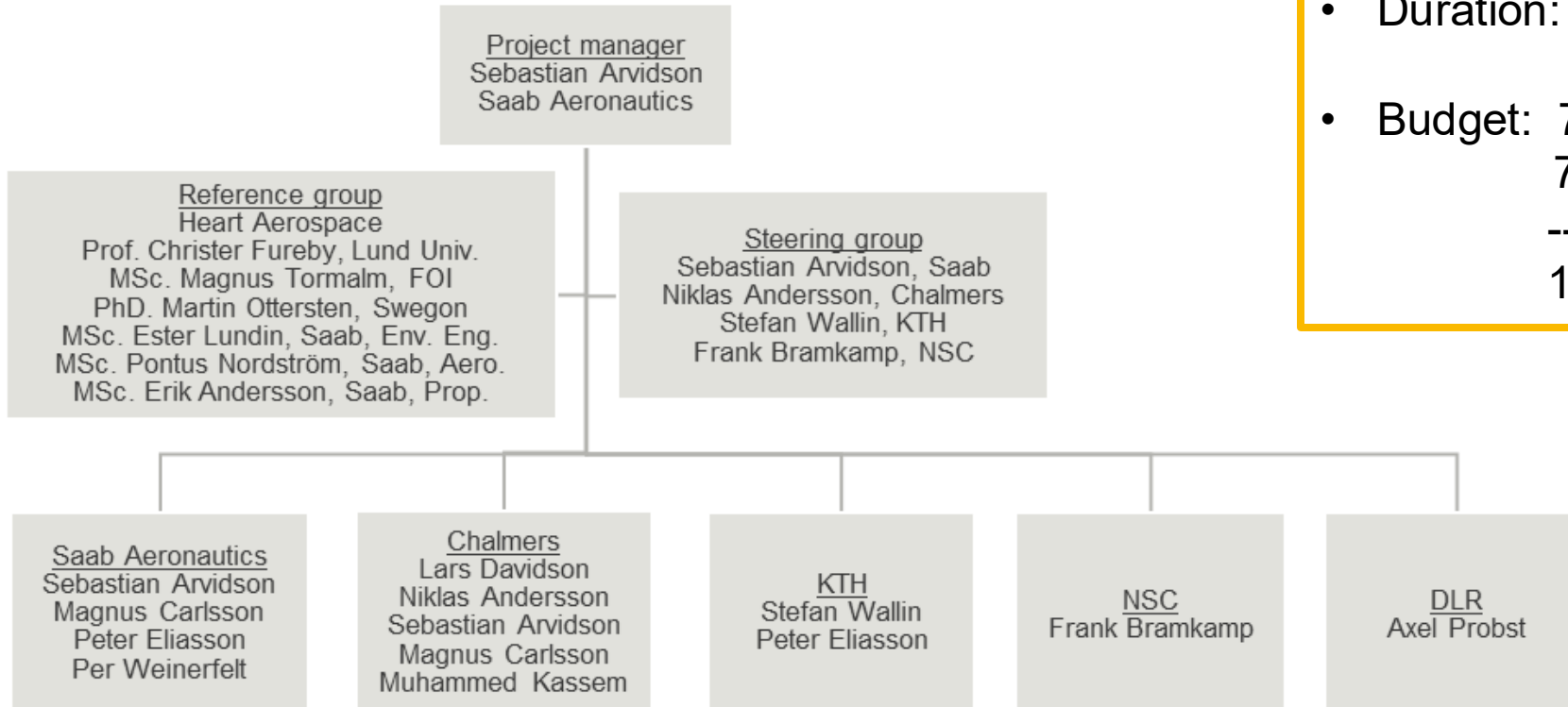
1. Adequate wall modeling with preserved accuracy but with improved efficiency in order to relax requirements on near-wall grid resolution as much as possible to minimize computational cost
2. High-quality numerical schemes to accurately capture resolved turbulence
3. Highly efficient flow solvers to reduce the computational execution time as much as possible
4. Statistical methods for uncertainty quantification to support user independent and improved quality of results based on turbulence-resolving methods

➔ *Formulation of the LESisMORE* research project*



*LESisMORE – “Large-Eddy Simulation In aeronautical applicationS; wall Modeling; rObustness, accuRacy and Efficiency”

LESisMORE – Project overview



- Funding: Vinnova
- Research programme: NFFP8
- Duration: Q3-2024 – Q2-2028

- Budget: 7.9 MSEK (Vinnova)
7.9 MSEK (Saab in-kind)

15.8 MSEK



SAAB



LESisMORE – Technical work packages



- Saab’s in-house solver M-Edge is used as the baseline solver to explore new algorithms, methods and approaches
- Exploration of new solver frameworks, based on the assessment in M-Edge, will be part of the project with the aim to design an efficient and fully GPU based turbulence-resolving CFD solver

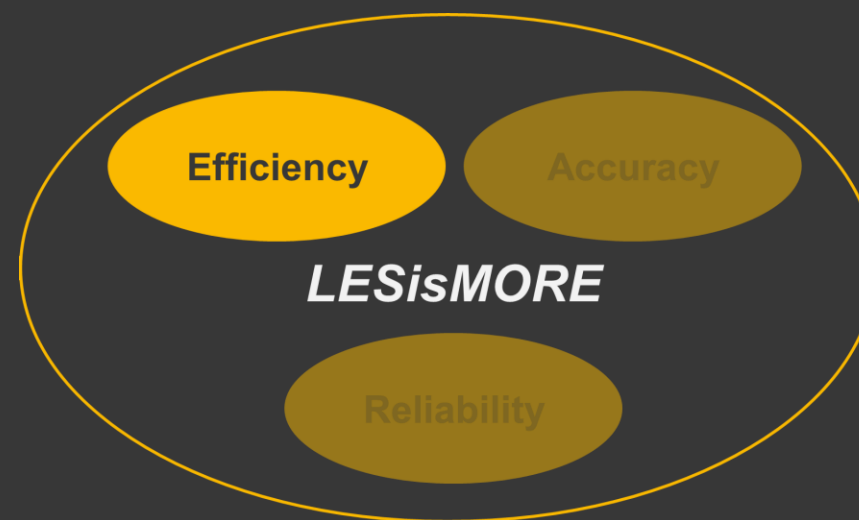
WP #	Title	2024		2025				2026				2027				2028	
		Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
1	Project management																
2	Machine-learning based wall modeling for LES																
3	Novel first principal wall modeling for LES																
4	Acc. and robustness of num. procedures for ind. LES-based flow sim.																
5	Improved efficiency using GPU																
6	Statistical tools for evaluation of LES-based flow simulations																
7	Demo of novel WMLES and large-scale LES-based computations																

Summary of the first year of *LESisMORE* activities



Novel first principal wall modeling for LES

Summary of the first year's activities

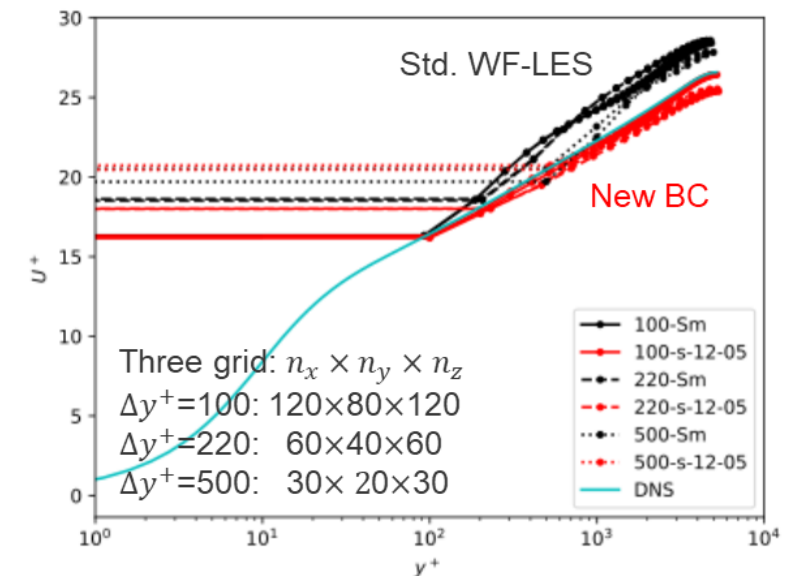
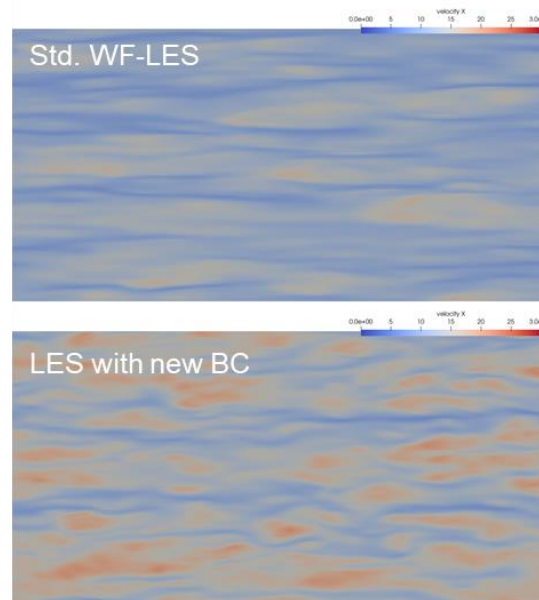


How coarse can we go?



- Coarse WM-LES – problems
 - Contaminated by “viscous” (=SGS) effects
 - Artificial low-Re streaks and buffer layer
 - Scales with computational $R_c^* = UL/(\nu + \nu_{SGS})$
 - May stay laminar
- Define low-Re surrogate setup
 - With $\nu^* = \nu + \nu_{SGS}$, slip BC and wall roughness
 - Find setup consistent with high-Re in outer scaling (Townsend similarity hypothesis, 1977)
 - LES redefined as DNS of surrogate setup
 - Interpreted as WM-LES with new wall BC
- New wall BC
 - Slip (Robin BC), $u_{i,w} = L_s(\partial u_i / \partial n)_w$
 - Non-zero wall-normal fluctuation, $v'_w \neq 0$
 - No log-law dependency

- LES results, new BC
 - Channel flow $Re_\tau = 5200$
 - Std. WF-LES: log-layer mismatch
 - **New BC**: Good match for all resolutions
 - Extremely coarse mesh, $30 \times 20 \times 30 = 18.000$ cells
 - Resolved turbulence stress and production at boundary
- Abstract submitted for TSFP14, 2026.



WM-LES, Channel flow $Re_\tau = 5200$, $120 \times 80 \times 120$ cells, $u_w(x, z)$ shown

Some more details



- New wall BC formulation

- Slip (Robin BC)

$$u_i = L_s \frac{\partial u_i}{\partial n}$$

- Slip length from Re scaling

$$L_s = C_S \Delta V_s^+, V_s^+ = \frac{1}{\kappa} \ln\left(\frac{v^*}{\nu}\right) + D^+$$

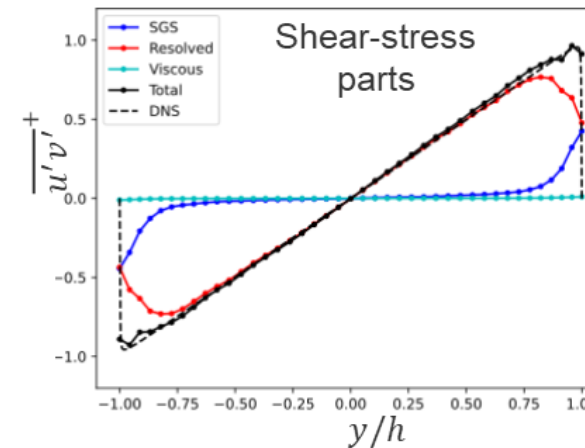
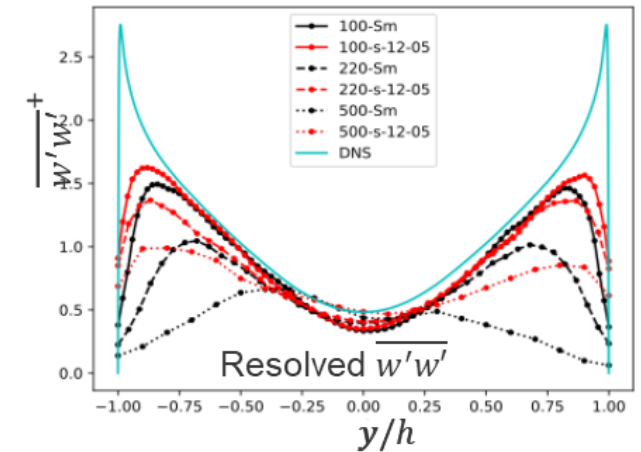
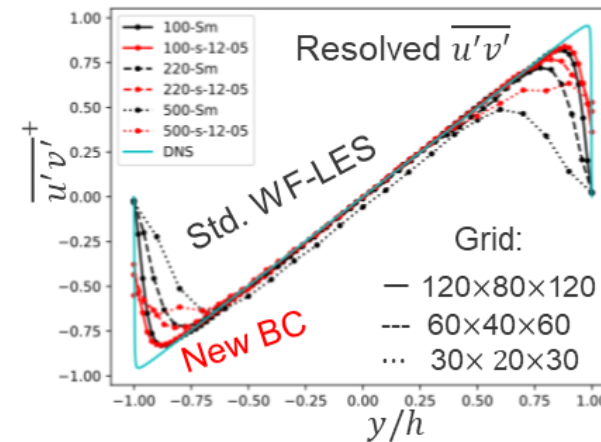
- C_S, Δ are Smagorinsky const. and filter
- D^+ is surrogate wall roughness

- Turbulence statistics

- New BC compared with std. WF-LES
- Non-zero **resolved** wall shear stress, balanced by less SGS stress
- Production of **resolved** turbulence at the boundary
- More resolved near-wall turbulence
- More spanwise w' fluctuations – more 3D turbulence

- Summary of new wall BC

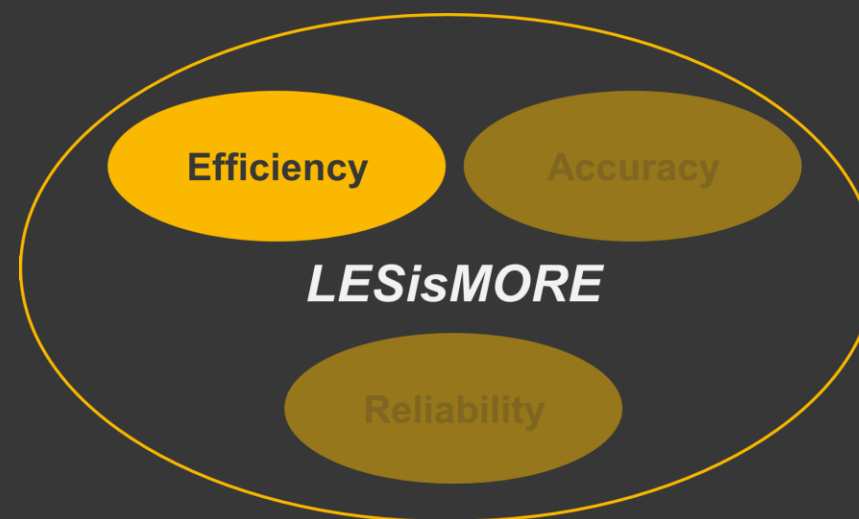
- Simple formulation – no log-law relation
- Allowed to interact with near-wall turbulence
- More physical near-wall turbulence
- Mitigated low- Re numerical buffer layer
- Scales with different resolutions (no recalibration)



Resolved turbulent stresses from fully developed channel flow, $Re_\tau = 5200$

Machine-learning based wall modeling for LES

Summary of the first year's activities



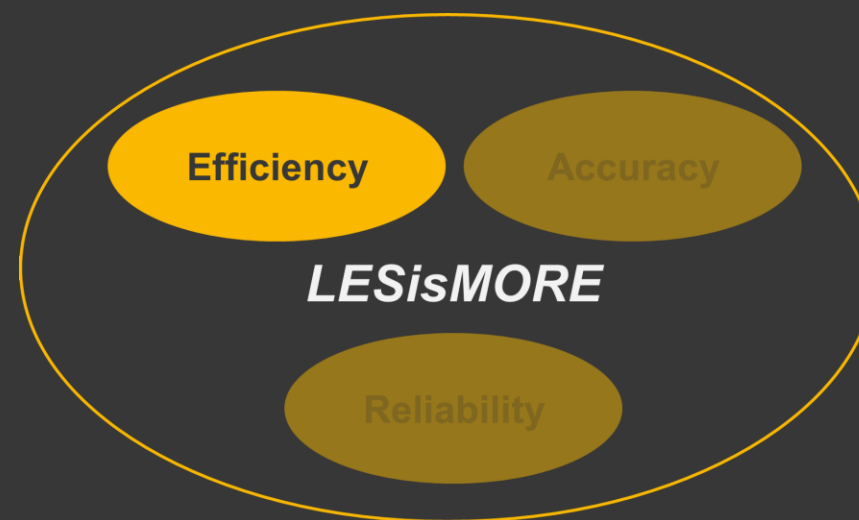
Initial studies on ML for LES wall functions



- New PhD student in the project – started in June 2025
- Exploration of machine learning methods to enhance wall functions for LES
- Literature study started with focus on
 - How wall functions are implemented in LES
 - How different types of machine learning models have been used to formulate wall functions for LES in the literature
 - Includes for example supervised learning but also reinforcement learning
- Mainly incompressible canonical flows in literature but also some compressible studies are presented

Improved efficiency of numerical procedures

Summary of the first year's activities



Efficiency enhancements of the Implicit solver



- Implicit formulation

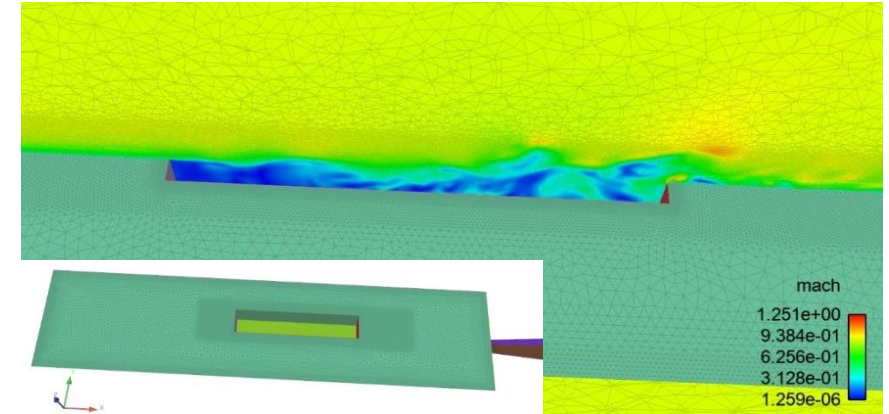
- Steady state problem: $V \frac{dq}{dt} + R(q) = 0$
- Implicit Euler backward \Rightarrow linear problem to solve: $Ax = b$

$$V \frac{q^{n+1} - q^n}{\Delta t} + R(q^{n+1}) = 0 \Rightarrow \underbrace{\left[V \frac{1}{\Delta t} + \frac{\partial R}{\partial q} \right]}_A \underbrace{(q^{n+1} - q^n)}_x = \underbrace{-R(q^n)}_b$$

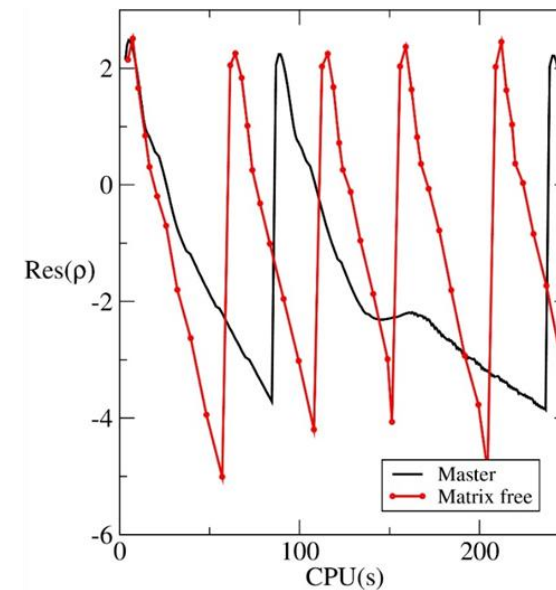
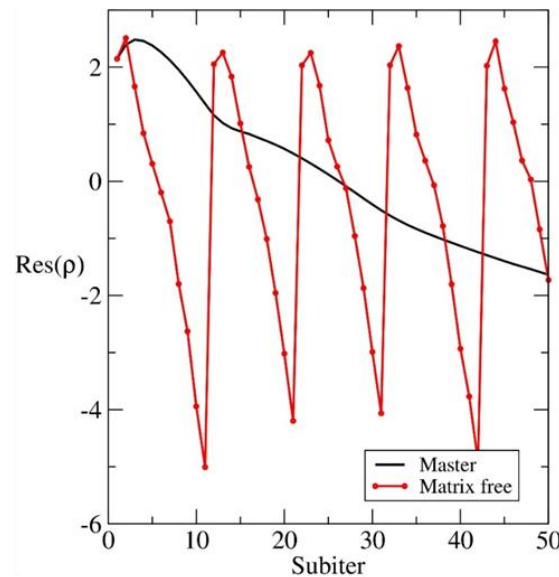
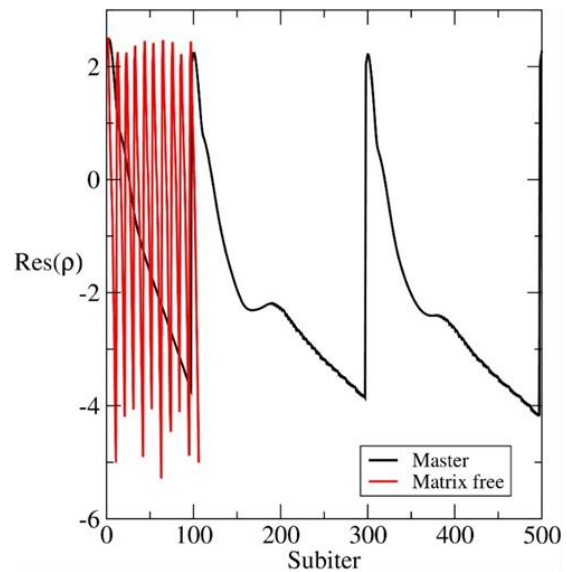
- Extended to unsteady calculations by dual time stepping (BDF2)
- Iterative solution technique
 - Preconditioned GMRES
 - Update $q^{n+1} = q^n + \omega x$ where $\omega \leq 1$ is an under-relaxation factor
 - Up to now – Jacobian A approximate and compact, $\omega = 0.5$
 - Newton like convergence requires
 - Jacobian A accurate, $\omega = 1$, $1/\Delta t \rightarrow 0$, i.e. CFL $\rightarrow \infty$
 - Accurate Jacobian A requires linearization of all terms in RHS
 - Alternative matrix free method: $Av \approx (R(q + \varepsilon v) - R(q))/\varepsilon$
 - Requires no linearization but more costly

Hybrid RANS-LES (DDES) of cavity flow

- M219, example with restart from fully developed flow
 - $M_\infty = 0.85, Re = 6.8 \times 10^6$
 - 64 partitions, 10 time steps
 - Implicit solution approach
 - Jacobian free - $\omega = 1, CFL = 10^7$
 - Jacobian (compact), $\omega = 0.5, CFL = 10^5$
 - Considerable speed-up with matrix-free approach



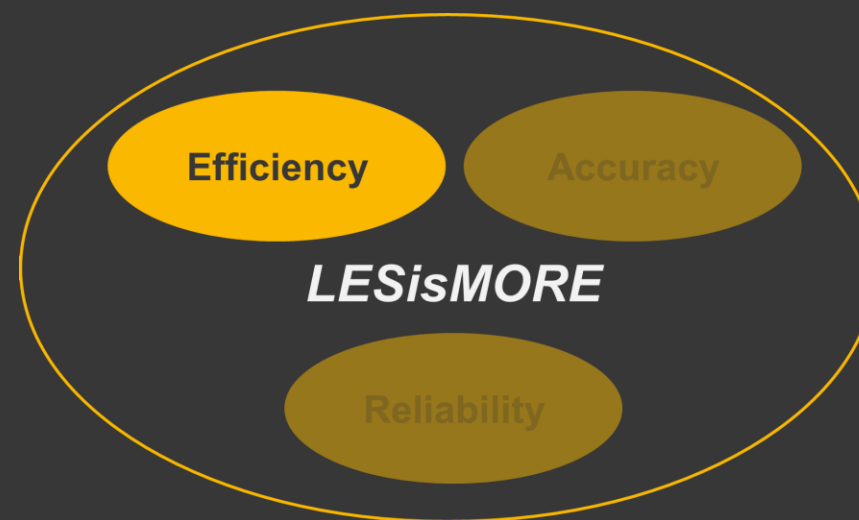
M219 cavity with grid and instantaneous flow field.



Efficiency enhancement using a matrix free approach.

Using GPU for efficiency enhancement

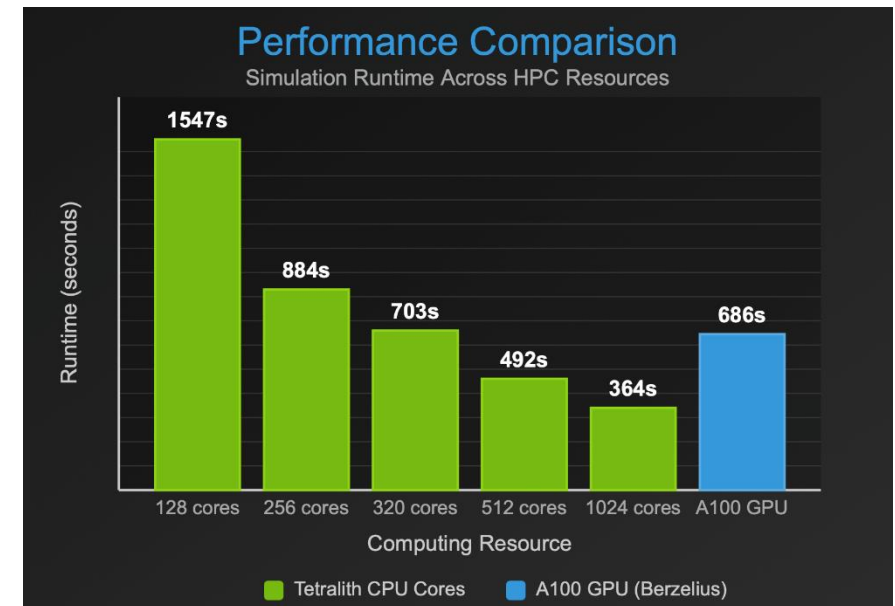
Summary of the first year's activities



Porting M-Edge from CPU to GPU – initial studies



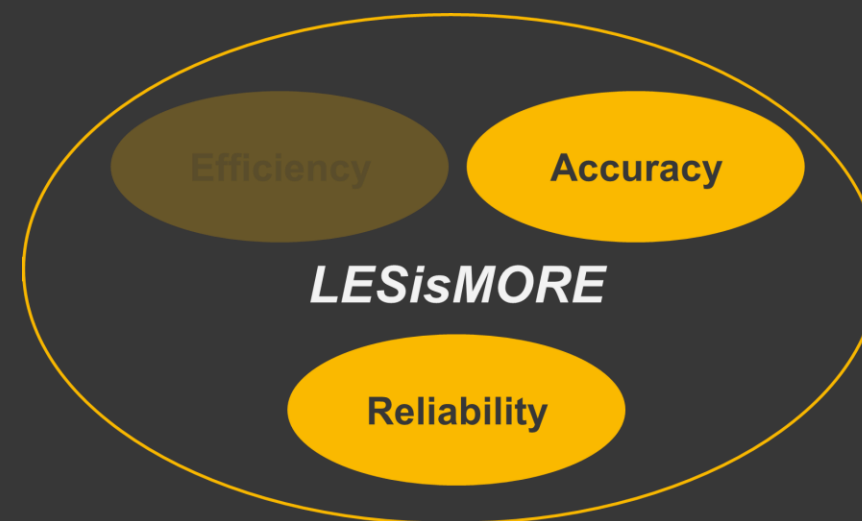
- Current M-EDGE GPU Programming Paradigm
 - M-EDGE: Fortran Code
 - Directive based approach using OpenACC
 - The first prototype to get experience in a reasonable time
 - Compiler support by NVIDIA and CRAY Compiler
- Preliminary results
 - Flat Plate, Navier-Stokes, Laminar Flow, 10 Mio. Nodes (2D to 3D extrusion of mesh)
 - Timing of 1000 iterations
 - **Tetralith**: Multi-node computation (CPU)
 - **GPU**: Single GPU, serial CPU version



M-Edge runtimes on CPU compared to GPU.

Improved accuracy and reliability of numerical procedures

Summary of the first year's activities



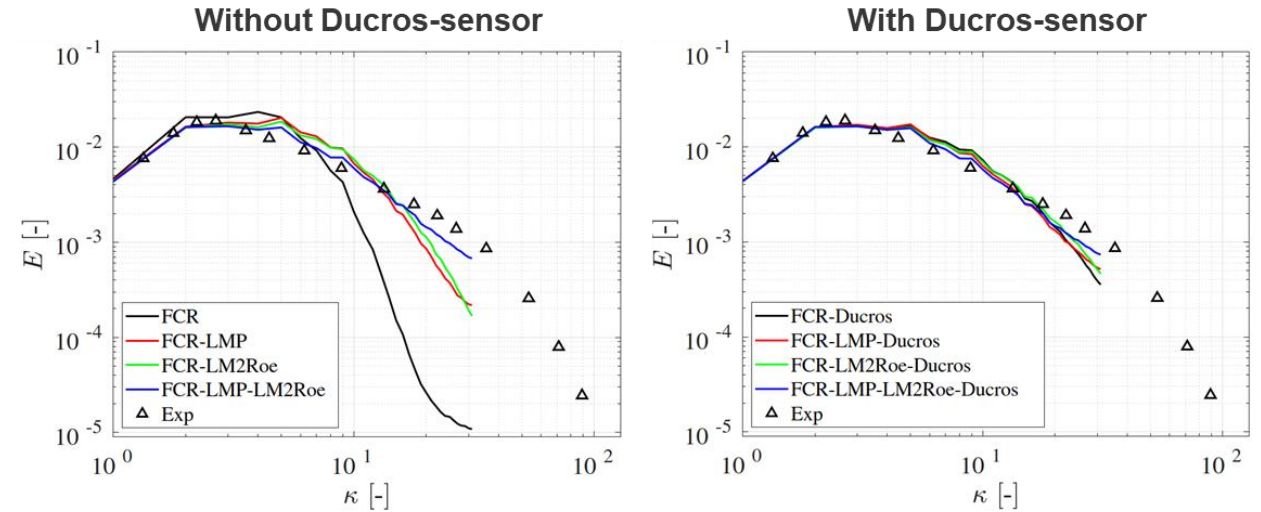
Accuracy enhancements convective flux



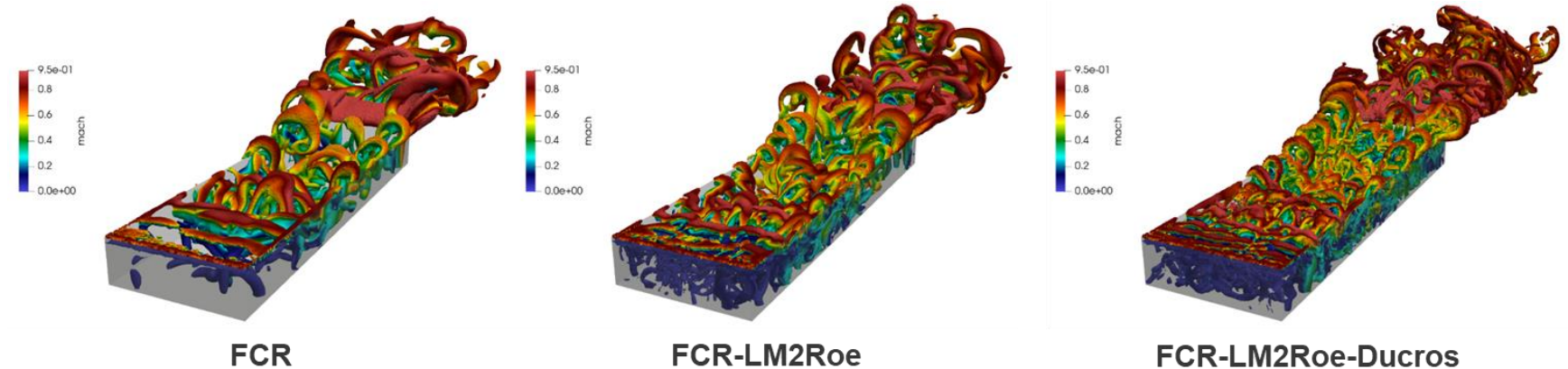
- Flux chain-rule (FCR) Upwind scheme
- $F_{jk}(\mathbf{n}_{jk}) = \frac{1}{2}(\mathbf{f}_L + \mathbf{f}_R) \cdot \hat{\mathbf{n}}_{jk} |\mathbf{n}_{jk}| - \frac{1}{2} \mathbf{D}(w_R - w_L) |\mathbf{n}_{jk}|$
- $q_L = q_j + \frac{1-\kappa}{2} \phi \nabla q_j \cdot \Delta \mathbf{r}_{jk}$, $q_R = q_k - \frac{1-\kappa}{2} \phi \nabla q_k \cdot \Delta \mathbf{r}_{jk}$
- $\mathbf{f}_L = \mathbf{f}_j + \frac{1-\theta}{2} \nabla \mathbf{f}_j \cdot \Delta \mathbf{r}_{jk}$, $\mathbf{f}_R = \mathbf{f}_k - \frac{1-\theta}{2} \nabla \mathbf{f}_k \cdot \Delta \mathbf{r}_{jk}$
- $\nabla \mathbf{f}_j = \left(\frac{\partial \mathbf{f}}{\partial q} \right)_j \phi \nabla q_j$, $\nabla \mathbf{f}_k = \left(\frac{\partial \mathbf{f}}{\partial q} \right)_k \phi \nabla q_k$
- κ and θ dissipation and dispersion parameters
- $\phi \in [0,1]$ primitive variables limiter for shock-waves
- Gradients computed using quadratic least-squares
- Low-Mach preconditioning (LMP) according to Choi-Merkle
- LM2-Roe
 - Reduce jump for velocities in dissipative flux
 - $u_L^* = \frac{u_L + u_R}{2} - \frac{z}{2} \Delta u$
 - $u_R^* = \frac{u_L + u_R}{2} + \frac{z}{2} \Delta u$
 - $z = \min(1, \max(M_L, M_R))$
- Ducros vorticity-shock-sensor
 - $\psi = \frac{(\nabla \cdot \mathbf{u})^2}{(\nabla \cdot \mathbf{u})^2 + (\nabla \times \mathbf{u})^2} \in [0,1]$
 - $\psi \approx 0$ in strong vortical motion
 - $\psi \approx 1$ in presence of shock-wave
 - $\tilde{z} = \min(z, \psi)$

Scale-resolving simulations

- DHIT shows that unmodified scheme FCR is too dissipative for scale-resolving simulation
 - Various Low-Mach modifications and vorticity/shock sensor can reduce dissipation to properly resolve turbulent structures
- Transonic cavity ($M_\infty \approx 0.8$) shows that Low-Mach modification is not enough to resolve turbulent structures in transonic flow
 - Ducros sensor reduces numerical dissipation in high-speed regions



DHIT. Effect of Low-Mach modifications and vorticity/shock sensor.



Transonic cavity flow. Effect of Low-Mach modifications and vorticity/shock sensor.

Summary and outlook

Summary



- An overview and the current status of the NFFP8 project *LESisMORE* has been presented
- The project aims towards applicability of LES-based simulations in the aeronautical industry on a daily basis
 - The main focus is on: wall modeling, efficiency, accuracy and uncertainty quantification
- After one year of activities improved accuracy and efficiency have been shown using
 - a variant of a *Flux chain-rule scheme* for unstructured grids in combination with a low Mach modification and a shock/vorticity sensor (accuracy)
 - a *matrix free formulation* for M-Edge's implicit solver (efficiency)
- A first step towards a GPU based solver has been taken using OpenACC with Saab's in-house solver M-Edge

- The project will continue to explore approaches with the aim to substantially reduce the computational cost for LES-based simulations
- Wall modeling to aggressively reduce the near wall resolution
 - Machine learning and first principle approaches for wall modeling in LES
- Alternative grid topologies in the near-wall region to relax grid resolution
 - Explicit time-stepping methods as a consequence of coarse near-wall grid resolution
- Exploration of alternative solver framework and data structures
- Algorithms Taylor made for GPU execution
- To benchmark efficiency, accuracy and reliability of methods, a common test case portfolio will be established

Thank you!

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Propulsion systems – concept & simulation
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